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INVESTIGATION OF DYNAMIC INTERACTION OF FIRE RETARDANT DROPLETS WITH FUEL, AND CORRELATION WITH THE RHEOLOGICAL PROPERTIES OF THE RETARDANT

TASKS 1 & 2. BASELINE AND PARAMETRIC VARIATION EXPERIMENTS

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TABLE OF CONTENTS

		Page
	SUMMARY	vii
1.	INTRODUCTION	1
	1.1 Scope of the Present Program	2
2.	BACKGROUND AND NATURE OF THE PROBLEM	2
	2.1 Droplet Sizes of Aerially-Dispersed Retardants	2
	2.1.1 Effect of the Physical and Rheological Properties of the Fluid	3
	2.1.2 Relation to Fuel Wetting by the Retardant	4
	2.2 Fuel Wetting by a Dispersed Retardant	4
	2.2.1 Liquid Storage on Fuel	5
	2.2.2 Effect of the Physical and Rheological Properties of the Fluid	6
3.	BEHAVIOR OF A LIQUID DROP IMPACTING WITH A DOWEL	9
	3.1 General Approach	9
	3.2 Experimental Setup and Procedures	10
	3.2.1 Dowel Weighing	10
	3.2.2 Splatter Pattern Observations	14
	3.2.3 High Speed Photography	14
	3.2.4 Fire Retardant Preparation	15
	3.2.5 Liquid Drop Preparation	15
	3.2.6 Prewetting Procedure	16
	3.2.7 Dowel Impact Angle	16
	3.2.8 Off-Center Impact	16
	3.3 Experimental Results and Discussion	16
	3.3.1 Liquid Retention on Dry Dowels After Normal Incidence Drop Impaction	16
	3.3.2 Effect of Dowel Impact Angle	23
	3.3.3 Effect of Prewetting the Dowel	24
	3.3.4 Liquid Spread Area on the Dowels	26
	3.3.5 High Speed Photographic Studies	28
	3.3.6 Discussion of the Splatter Patterns	35
	REFERENCES	48

LIST OF FIGURES

Figure	Title	Page
1a	Experimental Setup for the Dowel Weighing Experiments . .	11
1b	Scale Shield and Mounted Dowel	11
2a	Arbor Balance with Top Shield, Toothpick Stand and Test Dowel	12
2b	Setup for 45° Dowel Impact Test	12
2c	Drop Tower Used for the 42 ft Drop Tests	12
3	Illustration of the Liquid Mass Readings on the Arbor Balance vs Time	13
4	Experimental Setup for Photographing the Impact of a Falling Drop with a Dowel	14
5	Effect of Retardant Rheology, Dowel Size and Composition and Drop Height on the Liquid Retained on a Dry Dowel After Central Impact by a Medium Sized Droplet at Normal Incidence	18
6	Effect of Drop Diameter on the Liquid Retained on a Dry Dowel After Central Impact at Normal Incidence . . .	22
7	Comparison of the Liquid Retention at 0° and 45° Impact Angle	25
8	Comparison of the Liquid Retention on a Dry and Prewet 1/4 Inch Birch Dowel at Normal Incidence	25
9	Dowel Stains Produced on Birch Dowels by Medium Sized Drops	27
10	Spread Area of the Retardants on the Dry Birch Dowels After Impact	28
11	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel (42 ft DH)	30
12	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Birch Dowel	32
13	Blowups of the Side View Pictures of Figure 12	34
14	Selected Frames from the Impact of a Falling Drop of Fire-Trol 100 with a 1/2 Inch Birch Dowel	36

LIST OF FIGURES (Continued)

Figure	Title	Page
15	Selected Frames from the Impact of a Falling Drop of Fire-Trol 931 with a 1/2 Inch Birch Dowel	38
16	Selected Frames from the Impact of a Falling Drop of Fire-Trol 100 with a 1/2 Inch Polyethylene Dowel	40
17	Blowups of the Side View Pictures of Figure 16	41
18	Selected Frames from the Impact of a Falling Drop of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel	42
19	Blowups of the Side View Pictures of Figure 18	43
20	Splatter Patterns of Off-Center vs Central Impacts of a Falling Drop of Fire-Trol 931 on a 1/2 Inch PE Dowel	45
21	Splatter Patterns of Off-Center vs Central Impacts of a Falling Drop of Phos-Chek XA on a 1/2 Inch Birch Dowel	45
22	Splatter Patterns of Falling Drops of the Retardants Impacting Centrally with a 1/4 Inch Birch Dowel	46
23	Splatter Patterns of Falling Drops of Retardants Impacting with 1/4 and 1/2 Inch Birch and 1/2 Inch Polyethylene Dowels	46

LIST OF TABLES

Table		Page
I	Experimental and Theoretical Mass Mean Droplet Diameter of the Retardants	3
II	Liquid Retained on a Dry Dowel After Central Impact by a Liquid Drop at Normal Incidence	17
III	Approximate Values of the Fluid Properties of the Retardants	19
IV	Liquid Retained on a Dry Dowell After Central Impact by Small and Large Size Liquid Drops at Normal Incidence	21
V	Liquid Retained on a Dry 1/4 Inch Birch Dowel After Central Impact by a Medium Sized Drop at a 45° Angle . . .	24
VI	Liquid Retained on a 1/4 Inch Prewet Birch Dowel After Central Impact by a Medium Sized Drop	26

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SUMMARY

This report describes the results of an investigation of the impaction of individual drops of liquid fire retardant on fuel-simulating dowels, and the effects of the various parameters including retardant rheology on the interaction characteristics.

The studies were conducted by dropping individual drops of retardant with various droplet sizes and fall velocities (controlled by drop height) on different size and composition dowels under various conditions, and obtaining information regarding the impact by high speed photography, impactor cards that were located beneath and to the sides of the dowel, and measurement of the liquid mass retained on the dowel (by means of a sensitive scale). The retardants used in the studies were Phos-Chek XA, Fire-Trol 100, Fire-Trol 931 and water.

The tests showed that at the high (42 ft) drop height the percentage of the droplet mass that was retained on dry 1/4 and 1/2 inch birch and 1/2 inch polyethylene dowels after central (axis) impact by a medium sized (4-5 mm) drop of retardant at normal (0°) incidence was independent of the fluid composition. The liquid retention on the birch dowels increased with increase in dowel size, and for fixed dowel size the polyethylene was more efficient in retaining liquid than the birch. Decreasing the drop height (hence impact velocity) increased the liquid retention on the dowel, and the two Fire-Trol solutions and water had similar retentions. On the other hand the retention of Phos-Chek XA was significantly larger than the other fluids under this condition (low drop height). The high speed photographs indicated that in this case the fluid elasticity of the Phos-Chek retarded the flow and fracture of the liquid after impact so as to retain the liquid on the dowel; whereas the other liquids fractured freely during the impact flow which enabled more liquid to escape from the dowel.

Decreasing the drop size of the retardants increased the percentage of the liquid retained on the dowel (with other conditions fixed). However, it decreased the actual absolute mass of liquid retained in an impact, since small drops have less mass than larger ones. Increasing the impact angle increased the retention efficiency, but only slightly at the 42 ft drop height. The effect was about the same for all the retardants. The effect was much larger at the low (2 ft) drop height and in this case the retention of Phos-Chek was significantly greater than that of the other fluids, which were about the same. Prewetting the dowel with retardant had little effect on the liquid retention at the large drop height, but at the low height the effect was larger and the retention of Phos-Chek much greater than the other fluids.

The high speed photographs showed that at the 42 ft drop height, the impact of a drop of Fire-Trol 100, Fire-Trol 931 or water on a dowel initially produces a sheet of flowing liquid, which subsequently fractures cleanly along its width near the dowel. However, the sheet produced by the impact of a Phos-Chek XA drop does not fracture widthwise, but rather narrows (necks) down to a ligament as the flow continues. This behavior is believed due to the elastic nature of the flowing liquid, but the two different behaviors result in the same degree of liquid retention on the dowel.

On the other hand, at the low drop height the elastic nature of Phos-Chek XA retards the flow and (necking) fracture in a manner as to retain a much larger fraction of the liquid on the dowel than is retained of the other liquids, which fracture freely. In the case of the birch dowels, the liquid sheet produced by the high drop height impact flows laterally off the sides of the dowel for all the liquids. The same is also the case for the polyethylene dowel using Phos-Chek XA. However, Fire-Trol 100 differs in that the flowing liquid wraps around the dowel. This behavior may explain why polyethylene retains liquid more efficiently than birch at low impact velocities.

The impactor cards showed that for central (axial) impact on the dowel from the 42 ft drop height, the flowing and fracture of the liquid results in the formation of liquid fragments which are ejected laterally outward from both sides of the dowel and form a symmetrical splatter pattern. For the two Fire-Trol solutions and water these fragments consist of a spray of droplets, but for Phos-Chek XA the liquid mass is largely in the form of a coherent glob with few if any accompanying droplets. An off-center impact of the Fire-Trol solutions or water with the dowel produces a major coherent glob of liquid containing lateral outward instabilities together with smaller fragments, but Phos-Chek produces no smaller fragments under this condition. The splatter pattern is unsymmetrical. The position of the glob on the impactor card with respect to the dowel and the amount and degree of dispersion of the fragments depend on the impact position of the drop on the dowel. With increasing symmetry of the impact, i.e., in the direction of central (axial) impact, the major glob moves out from the dowel, and the dispersed fragments become more spray-like in behavior. In the case of the birch dowels the splatter is located at some distance from the dowel axis, which increases with increase in dowel diameter. On the other hand with the polyethylene dowel the splatter produced by Fire-Trol 100 (and presumably also for Fire-Trol 931 and water) extends into the axis of the dowel, indicating that in this case droplets are produced from the lower as well as the upper portion of the dowel. This presumably results from the wrap-around effect found for Fire-Trol 100 in the photographic studies, and in agreement with these studies was not found for Phos-Chek XA.

1. INTRODUCTION

The ability of a dispersed liquid retardant to suppress an advancing fire front in a fuel complex depends on the proficiency of the retardant droplets to wet or coat a large proportion of the fuel with a sufficient quantity of retardant salt. However the characteristics of the wetting-out process can depend on a variety of properties of both the fuel and the retardant droplets, and relatively little is known regarding the penetration, distribution and retention of the retardant as it interacts with different types of fuel elements, and the effects of the physical and rheological properties of the retardant on the various processes that occur during the overall wetting-out of the fuel.

Early studies by the U. S. Forest Service and others[1-3] (see also the references in ref. 1) provided evidence that the addition of a thickening agent to water or a liquid retardant can improve both the aerial drop characteristics of the fluid (by increasing the terminal droplet size) and the ability of the fluid to coat the fuel. However it was found that not all thickening agents act alike, and that certain types are clearly superior to others with regard to improving the dissemination characteristics of the fluid. The reason for the differences was not known, and the results led the Forest Service to sponsor a program with Shock Hydrodynamics whose overall purpose was to establish the relationships between the rheological properties of a fire retardant fluid and the aerial drop (dispersion) behavior and subsequent fuel-wetting capabilities of the retardant. The first of these objectives has now been attained[4-6] (to be discussed later).

On the other hand the results of the early field tests and continuing field experience with retardants have not provided clear or consistent evidence regarding the overall effect of retardant rheology on the wetting-out process. However these tests and experience together with laboratory and other studies (summarized in Section 9 of ref. 4) have demonstrated conclusively that retardant rheology can have an effect (whose relative importance however may depend on various conditions), and that these effects may be useful in controlling the wetting-out characteristics of the fuel in some situations. For example in fighting brush fires below tall crowned trees it is desirable that the dispersed retardant run off the tree crowns onto the ground cover; whereas for open (non-covered) fuel the retardant should stick directly to the fuel.

In preliminary studies conducted earlier on this program,[4-6] it was demonstrated that the impaction and flow characteristics of individual retardant droplets impacting on various surfaces depend on the rheological properties of the retardants. These studies indicated an approach based on high speed photography and sensitive weighing toward further understanding the dynamic interaction of retardant droplets with fuel, and correlation of the interaction effects and the accompanying fuel wetting with the rheological properties of the retardant.

The purpose of the present program then is to investigate the wetting-out characteristics of fuels by liquid fire retardant, based on the measurement and evaluation of the individual and cumulative effects that successive individual liquid drops have on the overall process. The objective is the elucidation of the effects of retardant rheology on the wetting-out process.

1.1 SCOPE OF THE PRESENT PROGRAM

The program consists of four general work tasks, and is designed to provide information regarding various aspects of the fuel wetting process ranging from the characteristics and affect of single droplet interactions with fabricated dowels to the cumulative effects of many droplets interacting (consecutively) with real fuel structures. In the first two tasks whose results are summarized in this report, information has been obtained regarding the behavior of single droplet impact with dowels including the effects of retardant rheology and droplet size, dowel composition, size and pre-wetting, and impact angle and orientation. Later studies (Task 3) will consider the effects of consecutive droplet interaction with 3-dimensional dowels that simulate actual fuel structure, and this will be followed by similar studies (Task 4) with real fuel structures. The results of the studies will be correlated with the controlling factors, including retardant rheology. On this basis a model will then be developed that characterizes the overall effects of retardant rheology on the wetting-out of fuels by a retardant rain.

2. BACKGROUND AND NATURE OF THE PROBLEM

The aerodynamic dissemination of a bulk liquid fire retardant results in the formation of a rain of the retardant which eventually falls on the fuel complex and causes a wetting-out of the fuel. This rain has a relatively short duration however (e.g., 5-15 sec), whose value depends on the droplet sizes (fall speed) of the retardant and the drop altitude. Large droplet sizes and small drop heights result in short settling times for the retardant cloud. During the settling, a quantity of liquid whose total eventual localized ground concentration ranges from less than 1 gpc* to values of 5 gpc or more - depending on conditions - falls on the fuel, which corresponds to about 0.016 to 0.08 inches of liquid (1 gpc is equivalent to about 0.01604 inches of liquid). The ground concentration of liquid retardant required to prevent fire propagation through a fuel complex depends on the type and concentration of the fuel, as well as other factors such as pattern width and wind conditions. For orientation purposes, the following quantities of a typical retardant have been deduced to be representative of the effective levels of retardant coverage required for various diverse fuel types:[7] tall grass (0.5 to 1 gpc), chaparral (4 to 5 gpc), crowned trees (2 to 5 gpc) and forest litter (3 to 4 gpc).

2.1 DROPLET SIZES OF AERIALLY-DISPERSED RETARDANTS

As noted before, retardants with different thickening agents form different droplet sizes when disseminated by an aircraft. The droplet sizes of water and several retardants were determined experimentally and

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*gpc indicates the localized surface concentration of liquid retardant in gallons per 100 square feet of ground area.

correlated theoretically on the earlier studies,[6] and are summarized in Table I for orientation purposes.

TABLE I. EXPERIMENTAL AND THEORETICAL MASS MEAN DROPLET DIAMETER OF THE RETARDANTS IN AND NEAR THE EFFECTIVE GROUND PATTERN (From ref. 6)

Retardant	Drop Speed (knots)	Mass Mean Droplet Diameter (mm)			
		Experimental*			Theory**
1.6 Phos-Chek XA	130	8.7	6.4±1.5	8.2	6.5
Phos-Chek XA	130	5.2	4.8±0.9	5.2	5.2
Phos-Chek XA	180	4.6	4.6±0.9	4.5	4.0
0.42 Phos-Chek XA	130	3.4	3.6±0.4	3.5	3.5
Fire-Trol 100	130	2.6	2.5±0.4	2.5	2.3
Fire-Trol 931	130	2.3	2.3±0.2	2.2	2.1
Water	130	1.6	2.0±0.4	2.0	0.6

* The three columns show the values obtained by three different methods of averaging the experimental data.

** The theoretical values are normalized to the experimental value obtained for 0.42 Phos-Chek XA.

The 0.42 and 1.6 Phos-Chek XA retardants are the standard Phos-Chek XA retardant in which the gum thickener concentration is a factor of 0.42 and 1.6 that of the standard formulation. The mean droplet size may thus be seen to increase with increase in thickener concentration. It decreases with increase in aircraft speed.

2.1.1 Effect of the Physical and Rheological Properties of the Fluid

On the basis of theory and some experimental data given in the literature it was deduced that the mean droplet size of the dispersed retardants at constant aircraft speed should vary proportionally with the quantity, $(\eta_e \sigma/\rho_l)^{1/3}$, where σ is the liquid surface tension, ρ_l is liquid density and η_e is the effective viscosity of the fluid given by[4]

$$\eta_e = \eta(1 + s) \qquad (1)$$

where η is the apparent viscosity and s is the elastic strain (recoverable shear) of the fluid. The value of η and s, and hence η_e, depends on the shear rate for a non-Newtonian fluid and hence the droplet size calculation must include the affect of the shear rate of the liquid during its aerodynamic surface stripping into droplets. Using the derived theoretical shear rate expression and the experimental η_e vs $\dot{S}$ data ($\dot{S}$ is the shear rate) obtained on the program gave quite good agreement between the theoretically computed mean droplet sizes of the various retardants and the experimental values, as may be seen in the table. The droplet size data given in the table are mass mean diameters. In the actual dissemination of a fluid a distribution of sizes about the mean value (both larger and smaller) are produced, and the various experimental and theoretical values are discussed in ref. 6.

2.1.2 Relation to Fuel Wetting by the Retardant

The preceding results explain the differences in droplet sizes obtained by the use of different thickeners. Thus for example, experimental measurements show that Fire-Trol 100 - which is a clay-thickened retardant - is a non-elastic liquid and its large apparent viscosity at low (Brookfield viscometry) shear rates is so reduced by shear during its aerodynamic stripping into droplets that its droplet size and drop characteristics are quite similar to water or unthickened retardant. On the other hand Phos-Chek XA - which is a gum-thickened retardant - is an elastic liquid, and the elasticity causes the effective viscosity of the fluid to remain relatively high during the droplet stripping process, which results in a much larger droplet size than for the Fire-Trol fluid. A gum-thickened retardant is thus clearly superior to a clay-thickened retardant insofar as the droplet size that is produced is concerned.

On the other hand there are a variety of processes that are involved during the wetting of a fuel by a retardant rain, and these may be affected in different manners by the viscosity, elasticity and surface tension of the liquid. Moreover the shear rates involved in these various processes may differ, and may change with time. In addition to the affects that these fluid properties may have on the fuel wetting by the retardant, the sizes of the falling droplets that interact with the fuel will be different for retardants with different properties, as just discussed. It is thus evident that the fluid properties - especially the rheological properties - may relate to the wetting-out of a fuel in a complex manner and that may depend on various conditions. It is the elucidation of this problem that the present program is concerned with.

2.2 FUEL WETTING BY A DISPERSED RETARDANT

Various studies have shown that the wetting-out of a fuel by either an ordinary rain[8] or an aerially dispersed retardant[7,9] occurs by a combination of droplet impact, run and drip. However due to the relatively short lifetime of a retardant rain, the fuel may not become completely or uniformly covered by the retardant. During the rain, the top portion of a fuel usually undergoes more direct interaction with the falling retardant

droplets than the bottom portion, which - depending on conditions - may receive most of its liquid by means of drip and run from the upper portion of the fuel. Depending then on the characteristics of droplet impact (e.g., liquid retention, splatter, etc.), the ability of the liquid to run and drip (related to fluid rheology) and the droplet size and duration of the retardant rain, the fuel will undergo wetting-out in a manner that at any time during the rain flow the coverage of the fuel by the liquid (and possibly the localized fluid concentration, e.g., film thickness) will vary, i.e., will not be uniform, in the vertical direction. Consequently the final liquid coverage (and localized concentrations) after the cessation of the rain and drip from the various elements of the fuel may also vary, and contain a gradient or maximum in the vertical direction. It is anticipated that this vertical distribution (and its time dependence) will depend - among other factors - on the rheological properties of the retardant.

2.2.1 Liquid Storage on Fuel

The accumulation and redistribution of liquid on the surface of a fuel during its wetting by a rain causes a storage of liquid on the fuel which will be partially or wholly retained after the cessation of the rain. This storage is often expressed in terms of an equivalent film thickness, as suggested originally by Grah and Wilson.[10] The equivalent film thickness is that average thickness of liquid that would be obtained if the liquid stored on the fuel were redistributed uniformly over all the area of the fuel. By conducting the storage experiment on a common fuel or fuel element (where the surface area remains constant) it is possible to measure the relative weights of different liquid retardants which can be stored on the fuel, and thus the relative storage effectiveness of liquids without the uncertainties inherent in the measurement of the fuel surface area.[4]

The amount of liquid that can be stored on a fuel depends on the conditions.[10] The storage of liquid on a saturated fuel subjected to a rain flow is called "transitory storage", and the value depends somewhat on the intensity of the rain. If the rainfall is stopped and the fuel allowed to drip until the excess liquid is removed, i.e., until the drip ceases, the term "conditional storage" is used to describe the storage. Finally if the fuel is shaken (corresponding to wind movement) to remove the loosely bound liquid, the term "residual storage" is used to describe the remaining stored liquid. This liquid is securely bound to the fuel and can only be removed by evaporation. For orientation purposes, it has been found in several studies involving the wetting of branched wood by a water rain that the percentage of liquid held by the fuel in storage is very roughly the same in each of the three storage conditions, i.e., about one-third of the total stored water under saturation conditions is subsequently lost by drip, an additional one-third is lost by shaking, and one-third remains firmly bound. This relative constancy does not appear to be valid for viscous retardants, however.

It has been found[4,9] (also in studies by the Forest Service) that the amount of liquid stored by a fuel, i.e., the equivalent film thickness, is significantly greater for a thickened retardant than for water (e.g., by

a factor of 4 to 15 depending on various factors). This is consistent with the statement that[1] "viscous agents were first incorporated in aerial and ground retardant formulations for the purpose of providing better adherence of the retardant to the fuels and to minimize the runoff". However gum-thickened retardants are elastic as well as viscous, and little is known regarding the relative importance of the viscosity and elasticity (which are both shear rate dependent) in the wetting-out of the fuel. It has been said that polymeric thickening agents add strength and consequently thickness to films applied to vertical fuel surfaces.[11]

2.2.2 Effect of the Physical and Rheological Properties of the Fluid

Studies have been conducted for some years to determine the effectiveness with which a fire can be extinguished by the direct application of water that contains an additive (called a short term retardant). For example, "wet water" is produced by the addition of wetting agents, e.g., certain detergents, which lower the surface tension so that the water can spread easier on a surface and also penetrate easier into smaller cracks. Of more importance however, are rheological additives (e.g., clays and certain gums and polymers) that increase the viscosity[12] and cause the water to stick or adhere more easily to the fuel, and be retained in greater thickness. Water thickened with these types of additives is sometimes called "viscous water", "sticky water" or "slippery water". In either of the above cases the main purpose of the additive is to increase the efficiency of the water in extinguishing the fire.

In the case of aerial fire fighting however, it has been found more effective to utilize retardant additives which themselves alter the ignition and combustion mechanism of the fuel in order to retard or prevent the flame spread. The overall better substances for this purpose have been found to be certain salts used as commerical fertilizers, including diammonium phosphate and ammonium sulfate. In this case the water is used largely as a vehicle to coat the fuel with the retardant salt - which is the dominant fire fighting ingredient - and the retardant is therefore called a "long term" retardant since the presence of the water is not necessary to retard the flame spread. In the use of the retardant, however, a rheological thickener is usually also added to increase the drop characteristics (droplet size) and improve the fuel-coating characteristics of the liquid retardant. The first of these, i.e., the effect of the thickener on droplet size is now understood in a semi-quantitative manner, as discussed previously.

The second purpose of the rheological thickener is to improve the retention of the liquid retardant on the fuel so that the requisite quantity of retardant salt is deposited on the fuel after the evaporation of the water. In this case the purpose of the thickener is related to that used in short term retardants except that the desired coating ability of the retardant is for the purpose of salt deposition rather than enhancing water layer

thickness (depending on various factors, both the retardant salt and water film may contribute to impeding the flame spread in the use of a long term retardant). The general effectiveness of a long term retardant in impeding flame spread is thus related to the wetting-out characteristics of the fuel by the retardant, and these characteristics are determined both by the physical and rheological properties of the liquid retardant (which are largely controlled by the thickening agent) and various properties of the fuel.

2.2.2.1 Vertical Fuel Coverage

As discussed before, fuel wetting by a water or fire retardant rain takes place by a combination of droplet impact, run and drip. During the wetting, a mass balance can be used to describe the partitioning of the falling liquid as it interacts with the fuel complex.[8] Thus of the total amount of liquid that falls on a fuel, a portion passes directly through the fuel without any interaction, another portion remains stored on the fuel while some passes through the fuel by means of drip and stemflow, and some liquid (but not the salt) may leave the fuel by evaporation. A variety of processes and factors are in principle involved in the wetting-out of a fuel by a retardant rain, but the general complexity of the events has prevented many of the individual processes to be taken into consideration in attempting to model the wetting of a fuel. For example, in most studies involving the wetting of forest fuels by rain the relative importance of the mass partition terms has been determined experimentally without regard to the various processes that occur and actually give rise to the partitioning. These studies have shown that the role of stemflow is usually of minor importance, and that depending on fuel conditions, the fraction of liquid that passes without interaction through the fuel can vary widely.

On the other hand it has been possible to take some of the preceding factors and processes into account in an indirect manner. Swanson and Helvig for example developed a vertical fuel coverage model as a method of providing estimates of the vertical fuel effect on required retardant quantities.[9] This model by-passed the actual processes involved in the droplet impaction, flow and drip of the liquid but took them into account in an indirect and approximate manner by utilizing the Grah-Wilson film concept of liquid storage. The characteristics of the wetting-out of the fuel in this model thus depend on the probability of direct droplet impact with the various elements of the fuel together with liquid transfer between various fuel strata by drip when the elements become saturated (in the Grah-Wilson film sense). The model can be calibrated from experimental data, and the effects of fluid rheology are included by the use of experimental film thicknesses of the retardants. This model is of some interest and predicts a number of realistic features of the wetting-out of a fuel by a retardant rain. It also has certain deficiencies.

It is well recognized that the physical and rheological properties of a retardant can affect the fuel-wetting process in various ways, even though the overall effects and how they change with conditions are not clear. For example these properties (at constant aircraft speed) determine the droplet sizes of the dispersed retardant, as discussed previously; and

different droplet sizes have different impact velocities. Both of these factors (size and velocity) affect the breakup of the droplet when it interacts with the fuel (as discussed in Section 9 of ref. 4), and should thus relate in some manner to the efficiency of the direct retention of the liquid by the fuel. For sufficiently small droplets which do not undergo breakup at impact the empirical equation of Sell[13] is often used[14] to describe the collection efficiency, E, of the droplets with diameter, D, impacting with velocity, V, with a cylindrical element with diameter d, i.e.,

$$E = 2.84(10^{-4})\ D^2V/d \qquad (2)$$

where E is %, D is microns, V is cm/sec and d is cm. On the other hand large drops passing through fine fuels such as tall grass may deflect the fuel and pass through intact. Between these extremes a droplet will breakup upon impact with the fuel and a portion of the liquid will be retained on the fuel element in the vicinity of the impact. Depending on various factors, the fraction of the liquid that is retained should depend on various properties of the liquid drop.

The droplet size can also have other effects on the fuel wetting process. Thus the size of the droplets will affect the chances of a droplet interacting with an element of the fuel during canopy penetration. The droplet size together with drop height also determine whether the retardant rain has a forward-moving component as it interacts with the fuel. Some studies have suggested[7] that a vertical rain is best for retardant application.

The physical and rheological properties of the retardant also affect the coating of the fuel (film thickness and coverage levels) as mentioned several times earlier, although the relative importance of the various properties (e.g., viscosity, elasticity, surface tension, bonding strength) are not generally known or how they depend on conditions. These effects are of special importance for fine fuels ($\leq$ 1/2 inch), since the effect of retardants on the retardation of flame spread is dominated by the fine fuels rather than the branch-woods.[9]

The fuel properties can also have important effects on the fuel-wetting capabilities of retardants. Anderson of the Forest Service conducted studies on the transmission of aerially-delivered fire retardant through vertical fuels.[15] He found that the fraction of retardant retained on the fuel increased as the fuel diameter and surface roughness of the fuel was increased. It is also known that surface composition, fuel geometry and other fuel properties can affect the wetting-out characteristics.

2.2.2.2 Retardant Rheology Tradeoff Considerations

As discussed earlier, a thickener is added to a fire retardant solution to improve both the drop characteristics (droplet size) and the coating of the fuel by the retardant. However these are independent

processes, and the optimum concentration of thickener is not necessarily the same for both processes. It is desirable in practice to adjust the thickener concentration in a manner as to achieve the best combination of retardant dispersion and fuel coverage, which however may vary somewhat depending on various factors. A suitable understanding of the effect of retardant rheology on the fuel-wetting process in conjunction with that presently available on the effect of retardant rheology on droplet size should enable the rheology tradeoff effects to be evaluated.

3. BEHAVIOR OF A LIQUID DROP IMPACTING WITH A DOWEL

As noted earlier, the purpose of this program is to investigate the wetting-out characteristics of fuels by liquid fire retardant, with the view toward elucidating the effects of retardant rheology on the wetting-out process. The general approach is based on the measurement and evaluation of the individual and cumulative effects that successive individual liquid drops have on the overall process. As a first step toward this goal, studies were conducted on the behavior of individual drops of retardant impacting with a dowel and are discussed in this section. Previous studies have examined the spreading characteristics of drop impact with a flat wood or paper surface,[4-6] and some preliminary information was also obtained using a wooden dowel.[5]

3.1 GENERAL APPROACH

The experiments consisted in dropping individual drops of retardant with various droplet sizes and fall velocities onto a dowel under various conditions, and obtaining information regarding the impact by high speed photography, impactor cards that were located beneath and to the sides of the dowel, post inspection of the event, and measurement of the liquid mass retained on the dowel (by means of a sensitive scale). The retardants used in the studies were Phos-Chek XA, Fire-Trol 100, Fire-Trol 931 and water, whose rheological properties encompass a wide range. An easily obtained medium drop diameter of 4 to 5 mm was used for all the retardants in many of the experiments, but in some studies small (~ 2 mm) drops were used in addition for the low viscosity fluids and large (7-8 mm) drops for the fluids with high viscosity. The impact velocity of the drops in many of the tests corresponded to that obtained by dropping the drops a distance of approximately 42 feet (from a drop tower) before they impacted with the dowel, which gave essentially full terminal velocity to the impacting drops. In some cases however the drops were dropped a distance of only approximately 2 feet to give a smaller impact velocity.

The cylindrical dowels used in the studies were made of 1/4 and 1/2 inch diameter smooth birch to simulate a fine fuel and study size effects, and 1/2 inch diameter polyethylene to study fuel composition effects. The dowels were positioned in the horizontal (0°) position, and also at 45° (with respect to the horizontal plane) to study the effect of impact angle. Both axis and off-center impacts were studied, and impacts were made on both dry dowels and dowels that had been prewet with the retardant (to simulate droplet impact after the surface had been wet by a previous impact).

3.2 EXPERIMENTAL SETUP AND PROCEDURES

The experiments were conducted by dropping individual drops of retardant onto a dowel that was mounted on a small stand. Except for the high speed photographic studies, the dowel was mounted on a sensitive scale in a manner that the liquid remaining on the dowel after the impact could be weighed immediately before any weight loss incurred by evaporation.

3.2.1 Dowel Weighing

The scale used for the dowel weighing procedure was the Arbor Model 506 Electronic Balance, manufactured by Arbor Laboratories Incorporated, and having dimensions of 16-3/8"x9"x10-1/2". A few of its special features include a digital readout, a tare function and a time integrator control that determines the length of time between display updates. Using the tare switch allows the reading of the liquid mass that is retained on the dowel after droplet impact. The capacity of the scale is 675 grams and its sensitivity is 1 milligram with a precision of 0.5 milligram.

In the experiments using the drop tower, the scale was placed inside a 2'x2'x3' plywood enclosure with a plexiglas front (see Figure 1a) to prevent airdraft from interfering with the scale readings. It was set on the concrete ground base to insure stability against vibration. The top of the enclosure contained an 11-inch diameter circular opening on which rested the 12-inch diameter, 40 foot long galvanized metal tube through which the liquid drops were dropped. The top of the tube was covered with a movable piece of plexiglas, which contained a 1.25-inch diameter hole through which the drops were introduced into the tube.

In order to prevent the scale from becoming contaminated with retardant when the falling drops missed the dowel and also allow only the liquid actually retained on the dowel to be weighed, a 0.035-inch thick metal shielding plate mounted on legs was used to cover the scale (Figure 1b,2). The plate contained two 1/4-inch diameter holes located 2-7/8 inches apart above the weighing pan of the scale through which two toothpicks supported the dowel (located above the shield) on its stand, which rested on the weighing pan. The tare weight of the toothpick stand was 9.419 gm.

3.2.1.1 Weighing Procedure

With the dowel weighing setup as shown in Figures 1 and 2, and using the tare function to give zero readings initially, when a drop impacted on the dowel, the individual weight readings on the readout versus time were plotted as illustrated in Figure 3. The initial high reading is due to the drop impact, and it is the subsequent plateau values that represent the weight of the retained liquid. In this particular case the weight of the retained liquid was considered to be 39 mgm. After sufficient time, the weight of the retained liquid would decrease, due to evaporation. The time at which this occurred as well as the rate of weight loss depended on various factors.

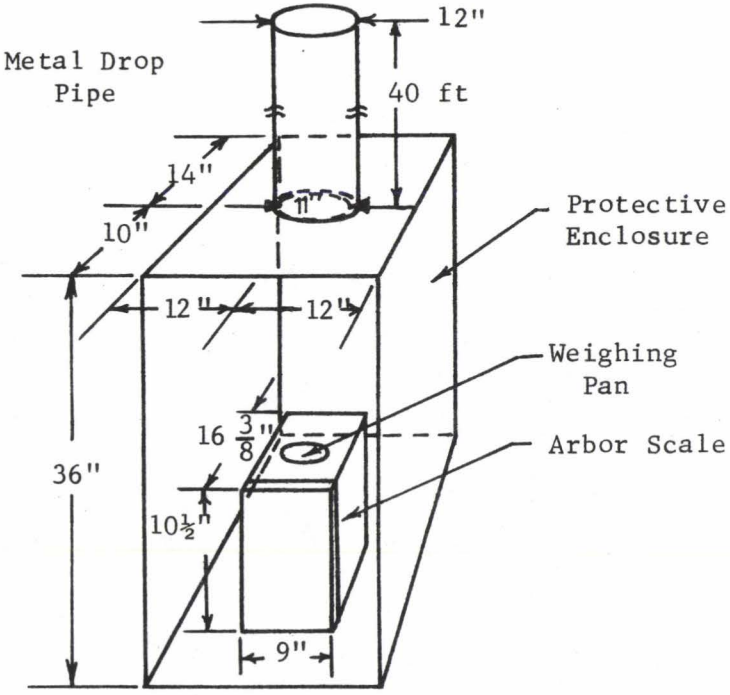


Figure 1a. Experimental Setup for the Dowel Weighing Experiments

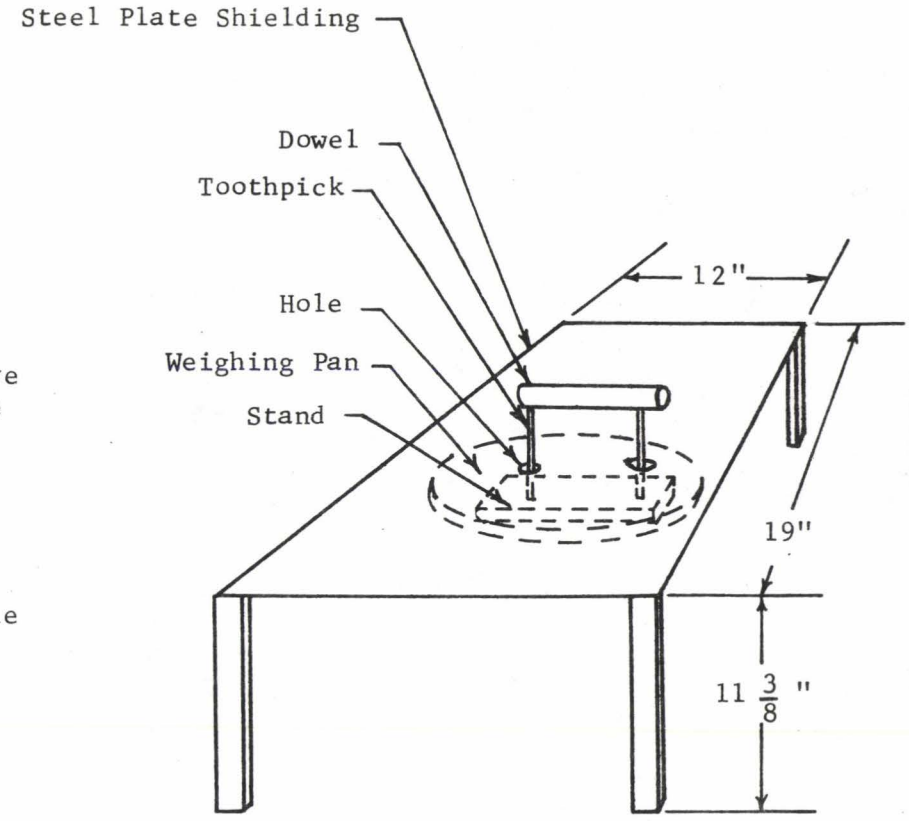


Figure 1b. Scale Shield and Mounted Dowel

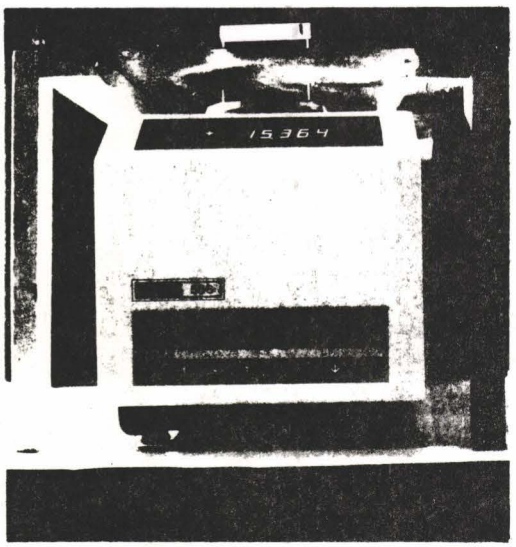


Figure 2a. Arbor Balance With Top Shield, Toothpick Stand and Test Dowel.

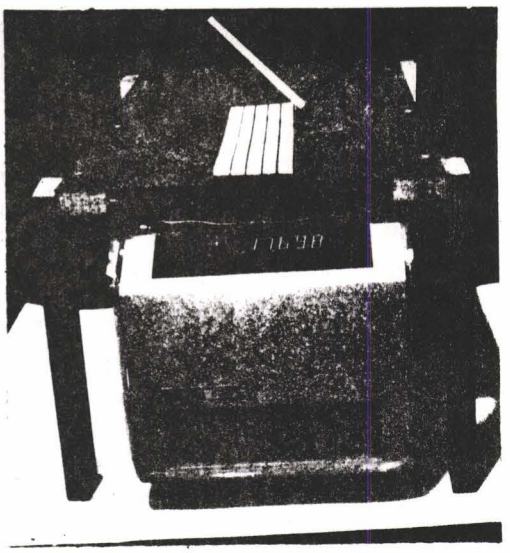


Figure 2b. Setup for 45° Dowel Impact Test.

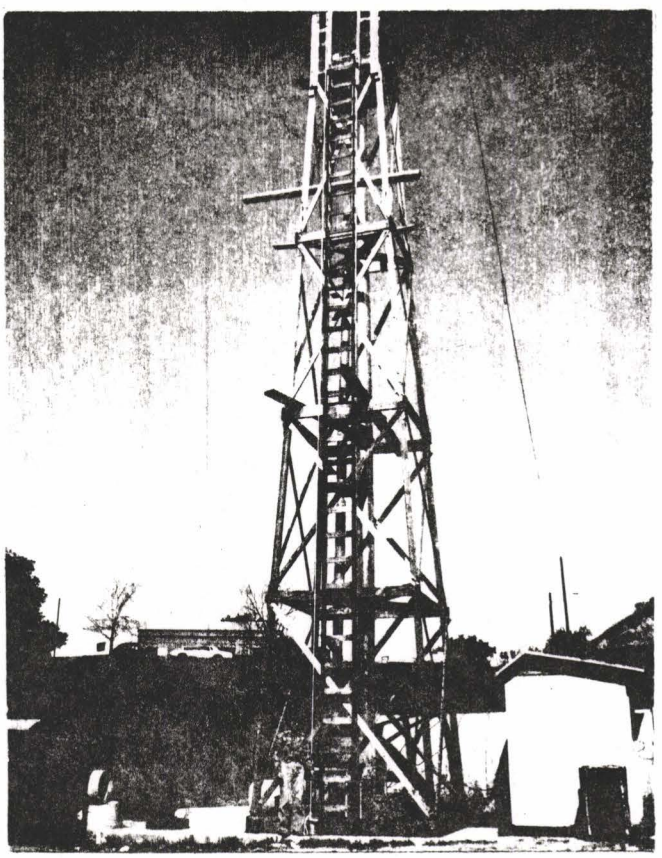


Figure 2c. Drop Tower Used for the 42 ft Drop Tests.

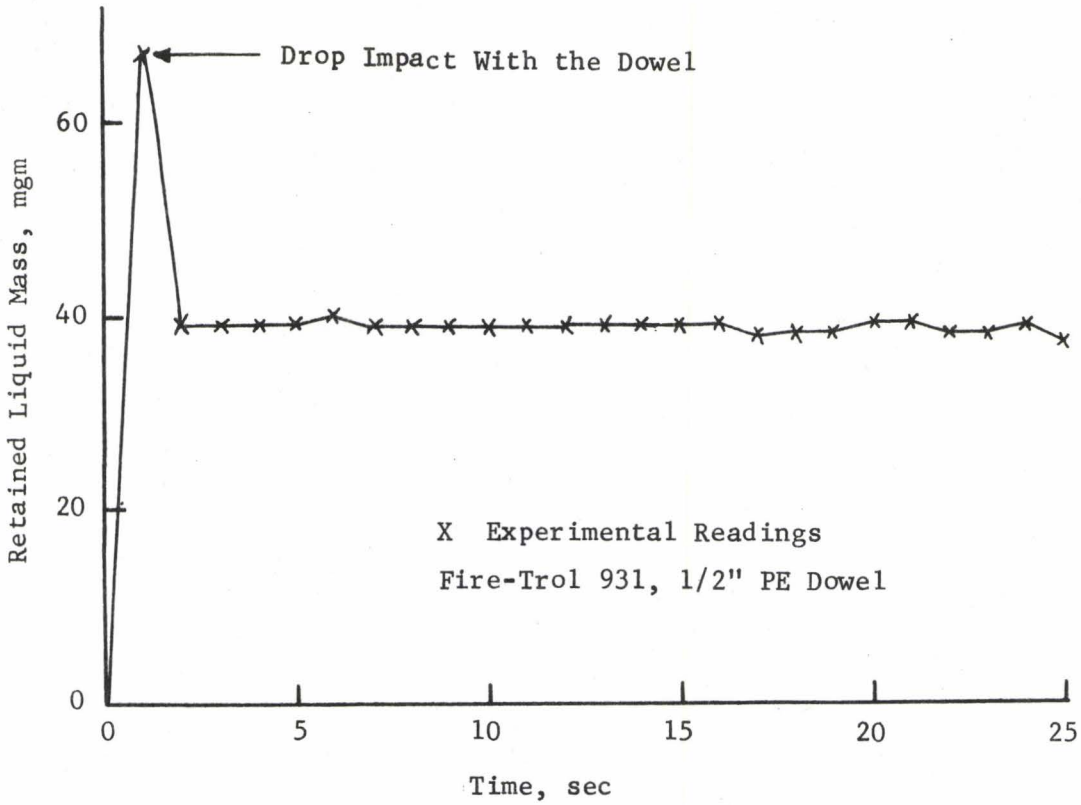


Figure 3. Illustration of the Liquid Mass Readings on the Armor Balance vs Time

3.2.1.2 Experimental Difficulties

Due to temperature gradients within the inside of the 40 ft long drop tube and possibly other factors, the drops usually did not fall straight down but rather appeared to follow a random (in some cases possibly spiral) path. With the setup as previously shown, and having the dowel lined up as well as possible with the dropper on the top, about 31% of the medium sized Phos-Chek XA drops hit the dowel in some position (i.e., off-center or central), but only about 5% of them hit the dowel on the center. About 70% of Fire-Trol 931 drops hit the dowel, off-center plus central, and only 9% of them hit the dowel on the center. Fire-Trol 100 was the hardest solution to aim, and only about 6% of the drops hit the dowel and 0.8% hit it on the center. A large number of drops were thus dropped in the studies, since about 3 to 7 successful impacts were obtained and averaged for each particular test condition.

At 2 ft drop height, the reduced drop height eliminated most of the drift and made aiming much easier. The percentage of central impacts in this case increased to 35% to 75% for the various retardants.

3.2.2 Splatter Pattern Observations

To obtain information regarding the splatter obtained from retardant droplets impacting with various fuel elements, an impactor (splatter) card of 8 x 2.5-inch dimensions, with 1/4-inch square drawn grid lines was placed centrally below the dowel. These cards were made of the same paper (glossy side up) as used in the studies of ref. 6. The splatter (or witness) card in a test was 2.5 inches below the top of the dowel, and rested on the steel plate. Thus its weight was not on the scale, which after a test enabled the weight of the liquid retained on the dowel to be determined.

The splatter card (and dowel stain) also provided evidence regarding whether a central (axis) or an off-center impact was produced in a test.

3.2.3 High Speed Photography

The high speed photography experiments were conducted to provide visual information regarding the behavior of a drop of retardant during its impact interaction with a dowel. In photographing the event, a photodiode was used to detect the droplet at some distance before it interacted with the dowel (Figure 4) and trigger the delay unit, which delayed the actuation of the flash lamp until just before the drop began to interact with the dowel.

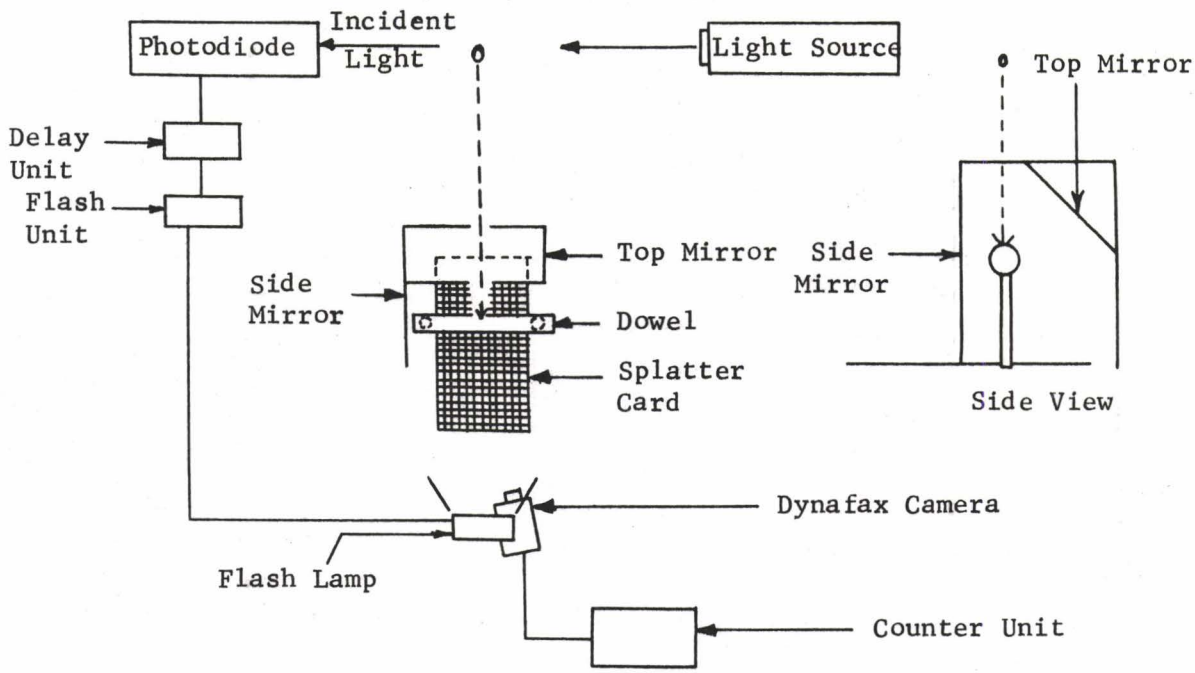


Figure 4. Experimental Setup for Photographing the Impact of a Falling Drop With a Dowel

A Dynafax camera was used to take pictures of the impact event, and a system of two mirrors was used which enabled the top and two side views of the target area to be photographed simultaneously. Under the experimental setup conditions, about 23 msec of the event could be observed photographically.

3.2.4 Fire Retardant Preparation

The retardants Phos-Chek XA, Fire-Trol 100 and Fire-Trol 931 were prepared in the same manner as in the previous programs.[4] The water used in studies was stained for visual purposes by adding 15 drops of India ink to every 50 mℓ of distilled water.

3.2.5 Liquid Drop Preparation

As noted before, three different sized drops (~ 2, 4-5 and 7-8 mm diameter) were used in the studies. Emphasis was given to the use of the medium sized drops, due to their relative ease of preparation. However some studies were also conducted with smaller and larger size drops of particular retardants in order to more closely simulate in some cases the actual mean droplet sizes produced in the field, as given in Table I.

The different size drops of the various retardants were obtained using different size eyedroppers. The ordinary eyedropper available commercially was used for the medium size drops, whereas the other two sizes were constructed by drawing glass to give the proper size orifice. Some difficulty was experienced in the preparation of the smaller drops in that the Fire-Trol 931 fluid occasionally tended to become clogged in the orifice, and the tips of the eyedroppers were fragile and broke easily during use. A 27 gauge hypodermic needle was also used to prepare the smaller drops of water in some cases, but could not be used for Fire-Trol 931 because of clogging.

In practice it was attempted to keep the generation of each drop as consistent as possible. The drop size of each retardant from a particular eyedropper was determined on each particular day that retardant was used by dropping about 10 or more drops individually from the top of the drop tower into a cup that was located on the weighing pan of the scale, weighing each drop and averaging the results. For example in one case, for the medium size drops of Fire-Trol 100, the individual drops weighed 71, 70, 68, 73, 73, 67, 68, 72, 71 and 68 mgm. The mean mass of a drop was thus 70.1 mgm, and the standard deviation was 2.234 mgm, or about 3.2% in droplet mass. Using the fluid density of 1.127 gm/cc, the diameter of the mean sized drops in this case was computed to be 4.92 mm.

The results were similarly obtained with the other retardants, but the percentage deviation from the mean was higher and ranged from about 6 to 12%, depending on the fluid and drop size.

3.2.6 Prewetting Procedure

In the prewetting experiments, the dowel was wetted with the retardant before it was impacted with a retardant drop. Since only a small percentage of drops hit the dowel, the prewetting liquid would evaporate during the drops, and consequently the chamber was kept humidified in these tests. Even so, it was sometimes necessary to repeat the prewetting during the dropping.

For water and Fire-Trol 931 the dowel was prewet by immersing it into the fluid and then shaking off the excessive clinging drops. This procedure was not used for Fire-Trol 100 and Phos-Chek XA due to their relatively large viscosity and consequent large film retention (much larger than the retention in the drop experiments). The procedure finally adopted for these retardants was to brush on the upper half of the dowel the amount of liquid mass that gave the same surface density of liquid as was obtained in the dry-dowel liquid retention experiments.

3.2.7 Dowel Impact Angle

The setup for the 45° dowel impact angle tests is as shown in Figure 2. The length of the dowels used in 0° impact angle case was 3 inches long. In order to have the same perceived length in the 45° inclination situation, the dowels used were approximatly 4-1/4 inches long. The splatter card was placed on the horizontal plane, thus making an angle of 45° with the dowel.

3.2.8 Off-Center Impact

Information on off-center impact was obtained along with the tests for central impact when the drop did not hit the dowel in the central position.

3.3 EXPERIMENTAL RESULTS AND DISCUSSION

3.3.1 Liquid Retention on Dry Dowels After Normal Incidence Drop Impaction

Several experiments were conducted for every test condition of the liquid retention studies, and the results were averaged. Table II summarizes the results of the liquid retention experiments on a dry dowel (3 inches long) with normal (0°) impaction by the medium sized (4-5 mm) liquid drops. Shown is the experimental average mass retained on the dowel for each test condition, the number of tests conducted for that condition, the standard deviation of the individual test results, and the percentage of the mass of the incident drop that was retained by the dowel after the impact. The results in Table II are shown graphically in Figure 5.

3.3.1.1 Impact Velocity

Two drop heights were employed for dropping the drops on the dowels; 42 ft and 21.3 inches (~ 2 ft). The impact velocity of drops of Phos-Chek XA and Fire-Trol 931 dropped from the drop tower was measured photographically

TABLE II. LIQUID RETAINED ON A DRY DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED LIQUID DROP AT NORMAL (0°) INCIDENCE

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.2-4.4	4.4-4.5	4.8-5.0	4.4-4.9
Drop Height:	42 ft	1/4 inch Birch Dowel		
Retained Mass, mgm	7.7	9.0	14.7	9.5
Standard Deviation	1.1 (7)*	0.8 (4)	1.5 (3)	0.6 (4)
Liquid Retention, %	20.5	18.1	20.9	17.8
Drop Height:	2 ft	1/4 inch Birch Dowel		
Retained mass, mgm	14.0	16.8	22.8	30.3
Standard Deviation	1.7 (3)	1.3 (4)	3.0 (5)	6.4 (4)
Liquid Retention, %	32.0	33.1	31.1	46.7
Drop Height:	42 ft	1/2 inch Birch Dowel		
Retained Mass, mgm	15.2	17.8	26.3	20.8
Standard Deviation	1.6 (5)	0.5 (4)	2.2 (4)	2.7 (6)
Liquid Retention, %	40.5	35.8	40.8	32.9
Drop Height:	2 ft	1/2 inch Birch Dowel		
Retained Mass, mgm	24.5	32.7	42.6	62.6
Standard Deviation	3.2 (6)	0.6 (3)	5.0 (5)	5.7 (5)
Liquid Retention, %	56.0	64.6	58.1	96.7
Drop Height:	42 ft	1/2 inch Polyethylene Dowel		
Retained Mass, mgm	26.9	34.8	—	33.8
Standard Deviation	3.3 (7)	3.7	—	3.4 (5)
Liquid Retention, %	71.5	70.2	—	72.5
Drop Height:	2 ft	1/2 inch Polyethylene Dowel		
Retained Mass, mgm	34.6	40.5	59.8	62.8
Standard Deviation	6.8 (5)	8.2 (4)	5.4 (5)	4.1 (6)
Liquid Retention, %	79.1	80.1	81.6	97.1

*The number in parenthesis indicates the number of tests.

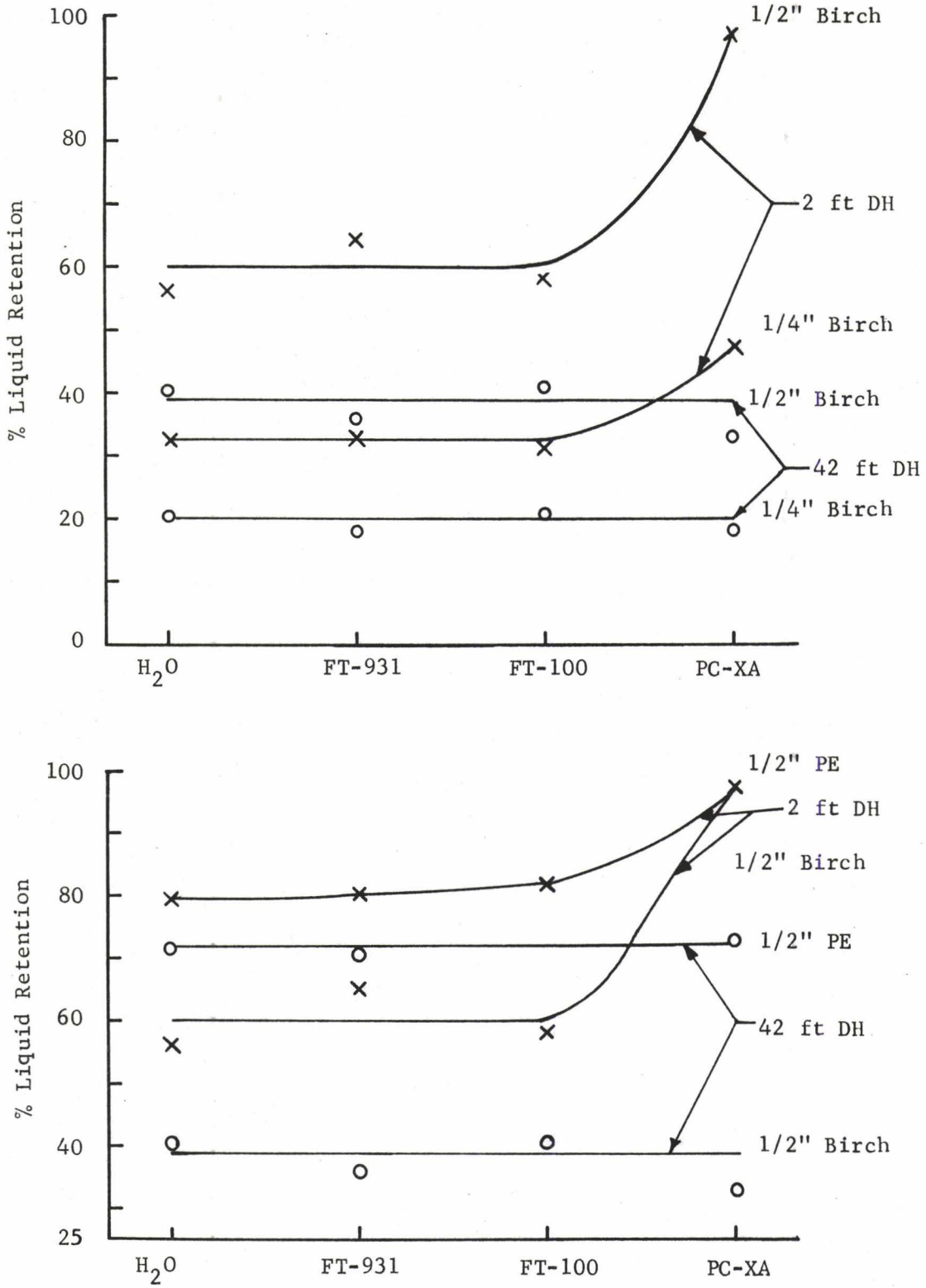


Figure 5. Effect of Retardant Rheology, Dowel Size and Composition and Drop Height (DH) on the Liquid Retained on a Dry Dowel after Central Impact by a Medium Sized Drop at Normal (0°) Incidence

and generally ranged between 26 and 27 ft/sec, which is close to the terminal velocity of the drops. Based on photography, the drops from the 2 ft drop height had an impact velocity of about 10.5 to 11 ft/sec.

3.3.1.2 Fluid Properties of the Retardants

In examining the implications of the experimental results it is useful to keep in mind the values of the various properties of the retardants. These were determined earlier,[4-6] and are summarized in Table III.

TABLE III. APPROXIMATE VALUES OF THE FLUID PROPERTIES OF THE RETARDANTS

Retardant	($\dot{S}$=12 sec^{-1})* η_a (poise)	η_e (poise)	($\dot{S}\simeq$ 550 sec^{-1})** η_a (poise)	η_e (poise)	Surface Tension (dyne/cm)	Yield Stress ($dynes/cm^2$)
Phos-Chek XA	13	37	1.0	12.5	46	185
Fire-Trol 100	19	19	0.6	0.6	92	235
Fire-Trol 931	1.3	3.3	0.085	0.5	80	20
Water	0.01	0.01	0.01	0.01	72	0

* This shear rate corresponds to the Brookfield value.

** This shear rate corresponds to the value at which the droplets are formed by the wind stripping of bulk liquid at an aircraft speed of 130 knots.

η_a is the apparent viscosity of the fluid, and η_e is the effective viscosity as given in Eq. (1). The apparent viscosity contains the combined effects of apparent viscosity and fluid elasticity at the particular shear rate at which process occurs. The shear rate over the more important range of the spreading and fracture of an impacting liquid drop will generally lie between the Brookfield and the surface stripping values shown in the table, but approaches zero near the termination of the flow.

3.3.1.3 Effect of Drop Height and Retardant Composition on the Liquid Retention

Figure 5 shows that at the 42 ft drop height the percentage of the liquid mass of a drop retained on each particular dowel after the impact was approximately the same for all of the retardants. This indicates that at high impact velocities the fluid rheology and surface tension have little effect on the liquid retention over the range of conditions studied. The reason for this is not known, but it implies that the effect of the visco-elastic and surface tension forces on the spreading and breaking of the liquid is small compared to the impact force which imparts a relatively high initial kinetic energy to the liquid.

On the other hand at a lower impact velocity (the 2 ft drop height) the percent of retention of the Phos-Chek XA on the dowel was significantly larger than the other fluids, whose retentions were about the same. The high speed photographs (to be discussed later) indicated that this was the result of the elastic forces developed in the liquid during its impact spreading, which resisted the flow and fracture of the liquid and tended to pull some of the spreading liquid back on the dowel subsequent to its peripheral fracture. This explanation is consistent with the fluid properties given in Table III which shows that Phos-Chek XA maintains a high effective viscosity over the shear rate range of interest (due to its elastic forces); whereas the effective viscosity of the two Fire-Trol solutions decrease significantly with increase in shear rate due to shear thinning, and the viscosity of water is naturally small (Fire-Trol 100 is a non-elastic liquid, and Fire-Trol 931 is slightly elastic).

The preceding results indicate that at relatively low impact velocities fluid elasticity can increase the amount of the liquid that is retained on the fuel. This is of some interest since liquid drip between various layered fuel elements is usually an important process in the wetting-out of a fuel by a retardant rain, and the impact velocities of the dripping drops are relatively small.

3.3.1.4 Effect of Dowel Size and Composition on the Liquid Retention

Figure 5 shows that at a constant drop height (impact velocity), the percentage of liquid retention increases with increase in dowel diameter. In fact, doubling the birch dowel diameter from 1/4 to 1/2 inches essentially doubled the liquid retention at both drop heights for all of the retardants. This effect is probably due to the increased surface area of the dowel that is in direct contact with the liquid during its spreading and subsequent fracture. Essentially all of the Phos-Chek XA drop remained on the 1/2 inch dowel at the low drop height.

The composition of the dowel can also affect the liquid retention (with all other factors remaining fixed). Thus it can be seen in the table that the percent retention was significantly greater for a 1/2 inch polyethylene dowel than for the 1/2 inch birch dowel at both drop heights, except for Phos-Chek XA at the low drop height which remained about the same since most of the liquid remained in both cases. The result that the retention was greater for the polyethylene dowel rather than less was somewhat surprising, since the plastic dowel was used to simulate a waxy surface such as smooth bark or a leaf. The increased retention of the polyethylene over the birch dowel is probably due in some manner to the difference in chemical bonding or wetting characteristics with the various retardants, since the plastic dowel had a smoother surface than the birch dowel.

3.3.1.5 Effect of Drop Size on the Liquid Retention

In addition to the studies using medium sized (4-5 mm) drops summarized in Table II, some studies were also conducted using both smaller (~ 2.3 mm) and larger (7.1 mm) sized drops of some of the retardants. The liquid retention results for normal incidence impact with a dry dowel are summarized in Table IV and Figure 6.

TABLE IV. LIQUID RETAINED ON A DRY DOWEL AFTER CENTRAL IMPACT BY SMALL AND LARGE SIZE LIQUID DROPS AT NORMAL (0°) INCIDENCE (DROP HEIGHT IS 42 FT)

Solution	Water			Fire-Trol 931			Phos-Chek XA		
Dowel*	¼" B	½" B	½" PE	¼" B	½" B	½" PE	¼" B	½" B	½" PE
Drop Diameter, mm	2.3	2.3	2.5	2.4	2.2	2.2	7.1	7.1	7.1
Retained Mass, mgm	3.5	5.0	7.5	3.5	4.7	6.0	18.0	35.7	61.4
Standard Deviation	0.7(2)**	0.0(2)	0.6(4)	0.7(2)	0.6(3)	0.0(3)	0.0(4)	4.0(3)	8.0(5)
Liquid Retention, %	53.5	75.2	96.5	45.9	77.8	100.0	9.0	17.8	30.6

* B and PE indicates the birch and polyethylene dowels.

** The number in parenthesis indicates the number of tests.

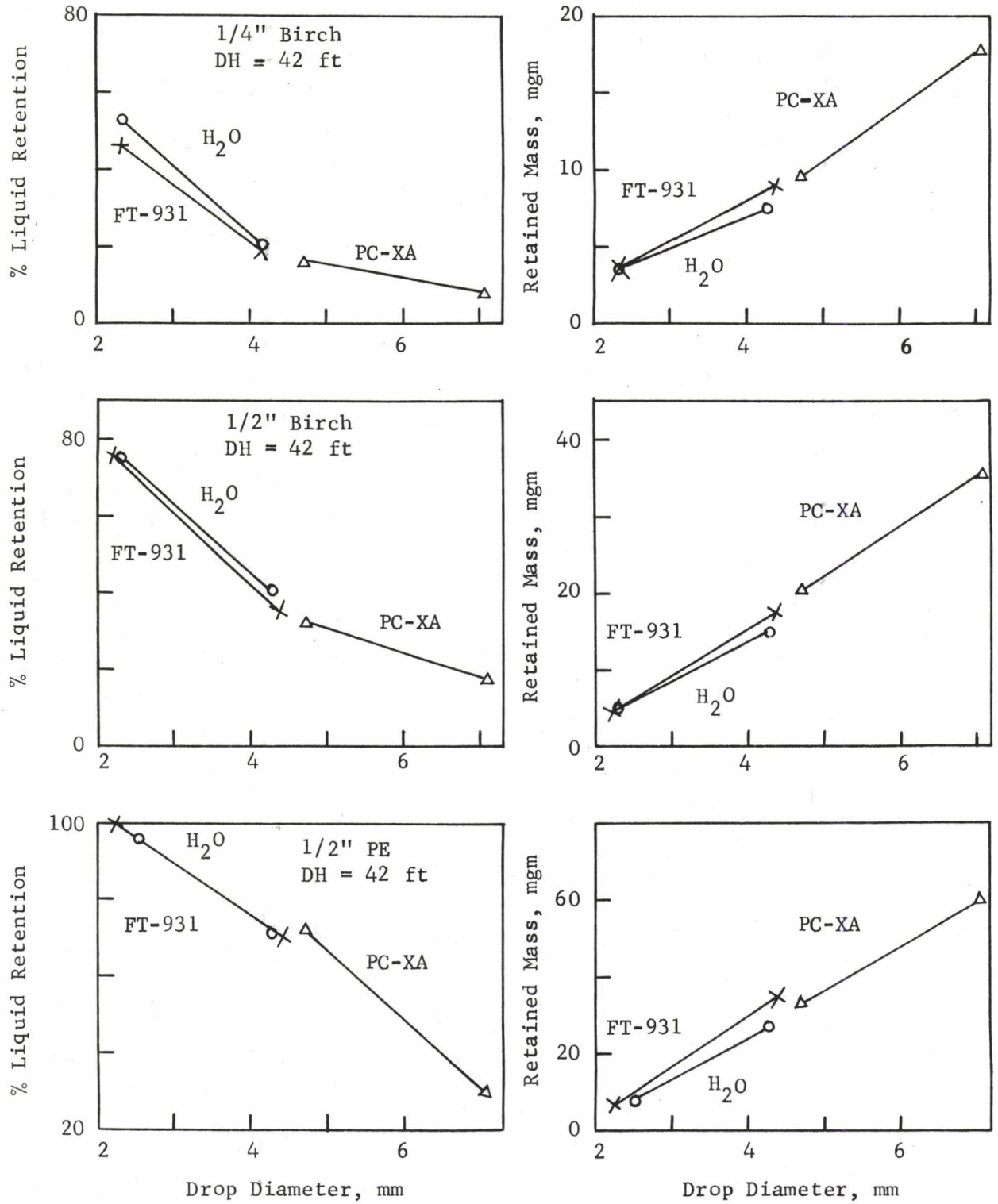


Figure 6. Effect of Drop Diameter on the Liquid Retained on a Dry Dowel After Central Impact at Normal (0°) Incidence.

A drop height of 42 ft. was used in these studies. The impact velocity of the drops was not measured in these cases, but can be estimated from the measurements on the medium sized drops and the effect of drop size on the terminal velocity. On this basis the impact velocity of the small and large sized drops was about 19 and 33 ft/sec, respectively.

A comparison of the results of Table IV with those of Table II (summarized graphically in Figure 6) shows that increasing the droplet size of a particular retardant (for fixed dowel size and drop height) decreases the percent of the mass of the liquid drop that is retained. However, although decreasing the drop size increases the efficiency of the liquid retention process, it decreases the absolute weight of retained liquid (shown also in Figure 6) since smaller drops have a smaller mass. Thus for example, although the percent mass retention of 2.3 mm drops of water on the 1/4 inch birch dowels was 53.5 percent, while the percent retention of 7.1 mm Phos-Chek XA was only 9 percent, the retained mass of the Phos-Chek was 18 mgm whereas the retained mass of water was only 3.5 mgm.

The general effect on the liquid retention of decreasing the droplet size while using a fixed size dowel is essentially the same as increasing the dowel size while using a fixed size drop, i.e., both changes increase the efficiency of the liquid retention process. The absolute value of the efficiency (% retention) depends on the relative size of the liquid drop in comparison to the dowel, as well as on retardant rheology and fuel composition. It is of interest to note (Figure 6) that small drops have a large retention efficiency with sufficiently large dowels (fuels) even at large drop heights.

3.3.1.6 Effect of Drop Size in Aerial Dissemination

As discussed in Section 2.1, different retardants have different drop sizes (see Table I) when dispersed from an aircraft. The studies summarized in Figure 6 show that the efficiency and absolute mass of the liquid retained on a dowel (fuel) after drop impact depends on the drop size. Thus in comparing the liquid retention characteristics of different retardants that are aerially dispersed, the actual drop size of the retardants should be used. On this basis the curves given in Figure 6 (using the appropriate drop size of each retardant) are more applicable than the curves in Figure 5 which are for constant drop size. Using the curves in Figure 6 shows that the liquid retention efficiency, i.e., the percent liquid retention of water and the two Fire-Trol solutions are then greater than that of Phos-Chek XA since their droplet sizes in the field are smaller. On the other hand the actual mass of liquid that is retained per impact is significantly larger for Phos-Chek XA than for the other fluids, but there would be less particle impacts (for constant dispersed retardant mass) because the drop size is larger.

3.3.2 Effect of Dowel Impact Angle

The effect of impact angle on the liquid retention efficiency was studied by positioning the 1/4 inch birch dowel at a 45° angle (with respect to the horizontal plane) as shown in Figure 2b, and discussed earlier. The results using medium sized drops and drop heights of 42 and 2 ft are shown in Table V, and compared with the normal (0°) results in Figure 7.

TABLE V. LIQUID RETAINED ON A DRY 1/4 INCH BIRCH DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED DROP AT A 45° ANGLE

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.1-4.3	4.3-4.4	4.8-4.9	4.8-5
Drop Height	42 ft			
Retained Mass, mgm	10.3	10.0	15.4	14.6
Standard Deviation	0.5(4)*	0.0(4)	1.5(5)	0.6(5)
Liquid Retention, %	28.5	22.2	24.3	23.5
Drop Height	2 ft			
Retained Mass, mgm	18.7	21.8	32.0	67.8
Standard Deviation	0.6(3)	1.2(4)	2.9(4)	11.5(4)
Liquid Retention, %	46.5	43.5	48.8	100.0

* The number in parenthesis is the number of tests.

It may be seen from Figure 7 and Table V that the general effect of increasing the impact angle is to increase the amount of liquid that is retained on the dowel, i.e., increasing impact angle increases the liquid retention efficiency. The fractional increase was not very large for the 42 ft drop heights (~ 20%) however, and was about the same for all the retardants with the possible exception of water which may have had a slightly greater value. On the other hand at the 2 ft drop height (lower impact velocity) the fractional increase of the liquid retention by increasing the impact angle from normal incidence (0°) to a 45° angle was quite large, and in the case of Phos-Chek XA allowed all of the liquid to be retained on the dowel.

3.3.3 Effect of Prewetting the Dowel

The prewetting experiments were conducted to simulate the effect of fuel wetting by previous droplet impact on the liquid retained by a succeeding impact. The experimental procedure was discussed earlier. The tests were conducted using a 1/4 inch birch dowel and the results are summarized in Table VI, and compared with the dry dowel results in Figure 8.

It may be seen from Figure 8 that at the 42 ft drop height prewetting the dowel had essentially no effect on the liquid retention, with the possible exception of water whose retention efficiency may have been slightly increased. On the other hand at the low drop height (low impact velocity), the prewetting increased the liquid retention of all the retardants significantly, with essentially all of the Phos-Chek XA being retained. As in the

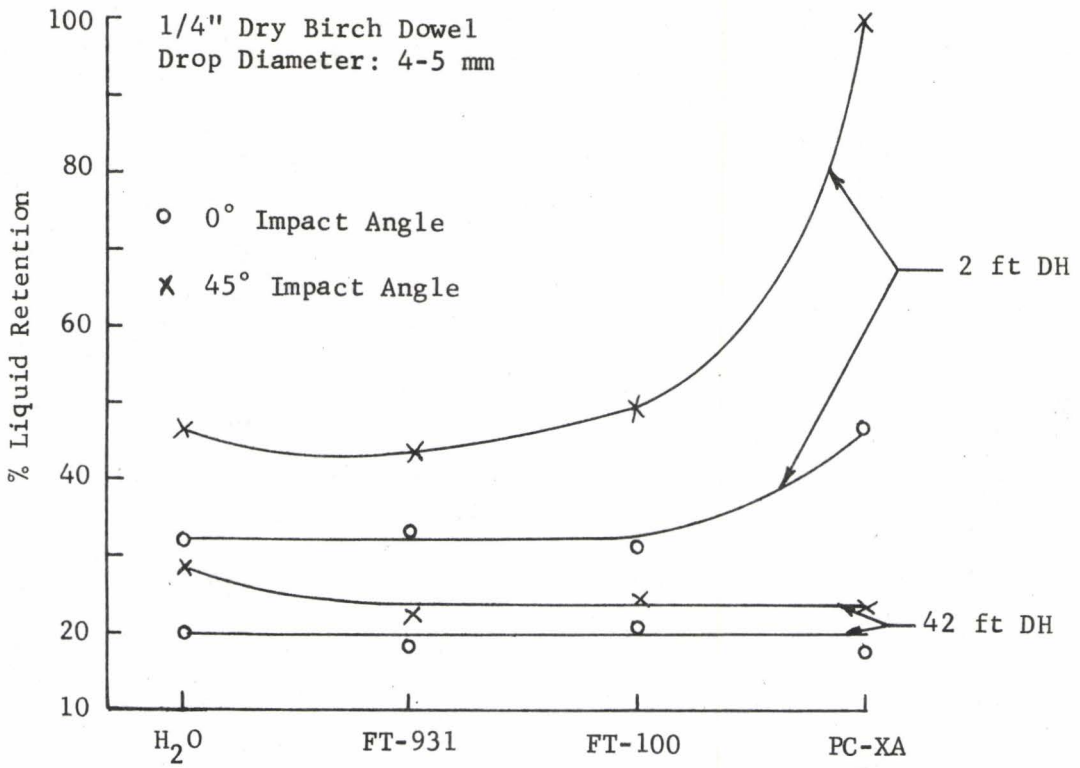


Figure 7. Comparison of the Liquid Retention at 0° and 45° Impact Angle

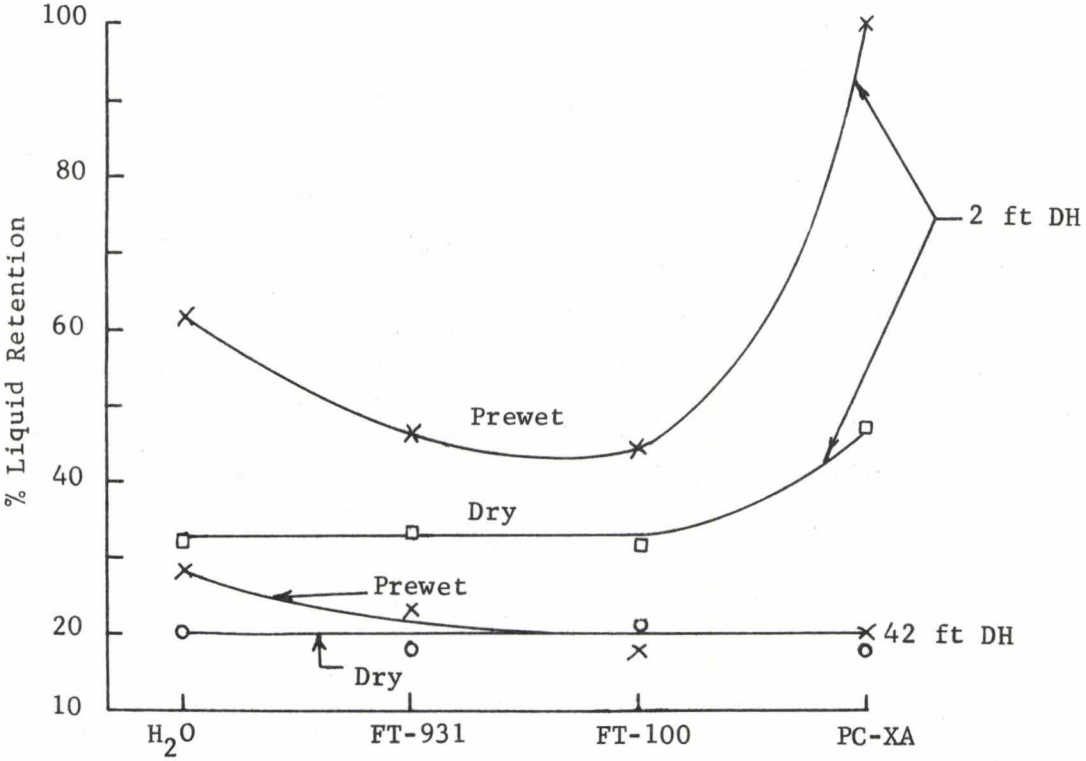


Figure 8. Comparison of the Liquid Retention on a Dry and Prewet 1/4 Inch Birch Dowel at Normal (0°) Incidence

case of the 42 ft drops, the retention of water appears to be greater than that of the two Fire-Trol solutions. The preceding results suggest that prewetting has a greater effect on enhancing the retention of liquid drip than of the rain drops during the wetting-out of a fuel.

TABLE VI. LIQUID RETAINED ON A 1/4 INCH PREWET BIRCH DOWEL AFTER CENTRAL IMPACT BY A MEDIUM SIZED DROP

Solution	Water	FT-931	FT-100	PC-XA
Drop Diameter, mm	4.2-4.3	4.4-4.5	4.8-4.9	4.9-5.0
Drop Height:	42 ft		0° Impact Angle	
Retained Mass, mgm	11.7	11.7	12.8	14.0
Standard Deviation	0.6 (3*)	1.2 (3)	2.6 (4)	1.4 (4)
Liquid Retention, %	28.1	23.0	17.8	20.2
Drop Height:	2 ft		0° Impact Angle	
Retained Mass, mgm	25.2	23.0	29.8	69
Standard Deviation	1.5 (4)	1.4 (2)	3.1 (6)	6.4 (5)
Liquid Retention, %	61.5	46.0	43.7	100.0
*The number in parenthesis indicates the number of tests.				

3.3.4 Liquid Spread Area on the Dowels

The stains left on the dowels after drop impact were roughly rectangular in shape, with some small rays occationally emerging in both axial directions (in the 45° impacts the rays were directionalized in the direction of fluid flow). The distance around the dowel circumference on either side of the central impact point that the stain penetrated depended on the size of the drop with respect to the dowel. The stains left by the colored water and Fire-Trol 100 on the birch dowels were usually essentially uniform (Figure 9). On the other hand the stain left by Fire-Trol 931 was generally slightly nonuniform and contained some pockets. This was also true of Phos-Chek XA but to a little larger degree. The stains left on the polyethylene dowels were always nonuniform for all the retardants, and the liquid was retained on the dowel in the form of small globs and strings.

The rectangular arcing shape of the stains on the birch dowels made it possible to measure the spread areas produced by the impacts. Figure 10 shows these spread areas for several cases of interest.

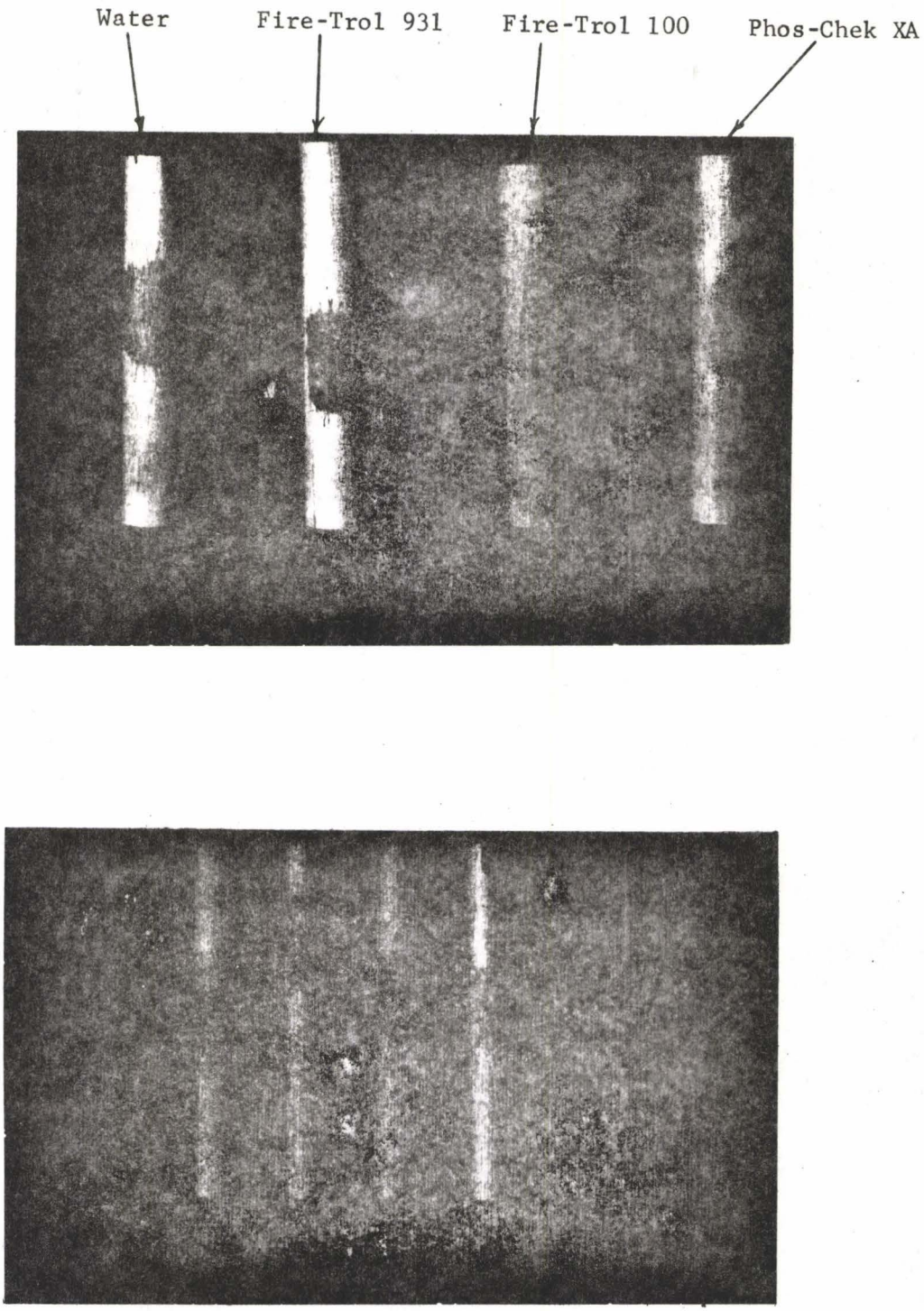


Figure 9. Dowel Stains Produced on 1/4 and 1/2 Inch Birch Dowels by Medium Sized Drops. (Drop Height = 42 ft).

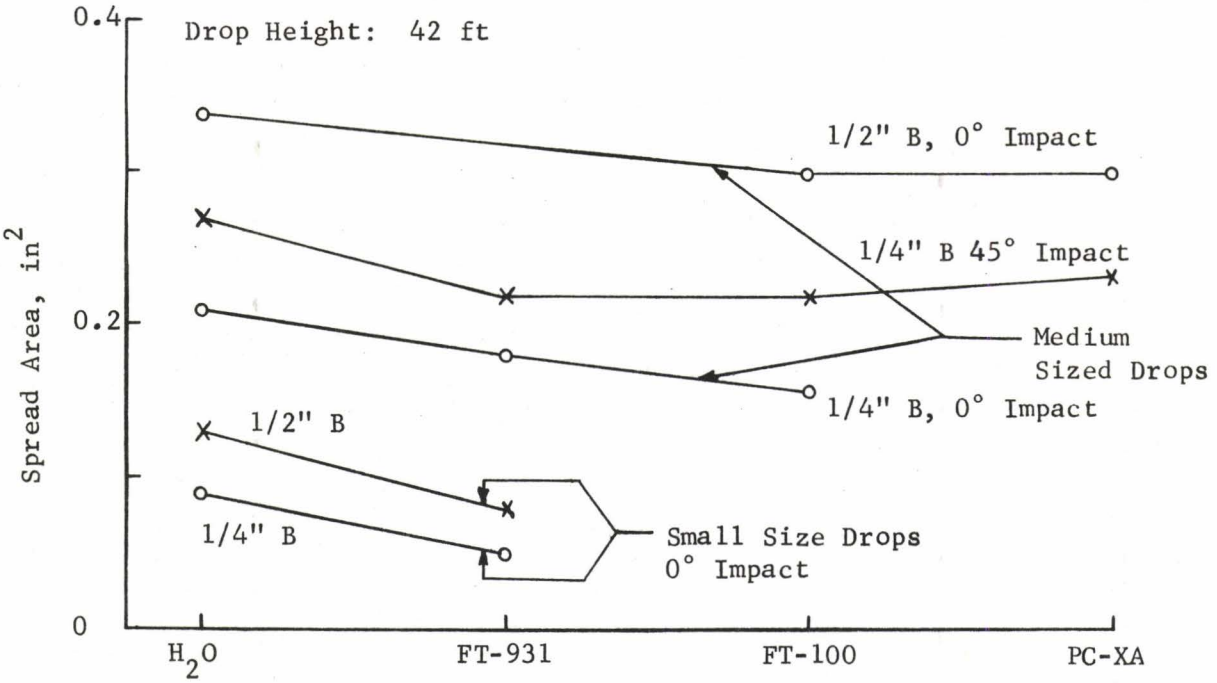


Figure 10. Spread Area of the Retardants on the Dry Birch (B) Dowels After Impact

It is seen that the spread area is larger for larger drop size, dowel size and impact angle. Using the spread areas in this figure and the corresponding measured values of the liquid retained on the dowel allows estimates to be made of the average film thickness produced by the impacts. For example, the estimated film thicknesses produced by medium sized drops impacting at 0° on a 1/2 inch birch dowel are: Water, $2.73(10^{-3})$ inch; FT-931, $3.11(10^{-3})$ inch; FT-100, $4.75(10^{-3})$ inch and PC-XA, $3.97(10^{-3})$ inch.

3.3.5 High Speed Photographic Studies

As discussed earlier, high speed photographs of the drop impacting with the dowels were taken in selected cases to help provide information regarding the impaction process. The experimental setup was discussed in Section 3.2.3.

In ref. 5, high speed photographs were given of a medium sized (4-5 mm) drop of Phos-Chek XA impacting centrally (after a 40 ft fall) on a 1/8-inch diameter birch dowel, and a drop of Fire-Trol 100 impacting on a 1/4-inch diameter dowel. It was found that the liquid initially tended to spread and flow laterally off both sides of the dowel in the form of a sheet. In the case of the Phos-Chek the sheet narrowed (necked) as the flow continued and ultimately became a ligament near the end of the event. This necking behavior was believed to be due to the elastic nature of the flowing liquid. On the other hand, although the initial phase of the spreading for Fire-Trol 100 (which is shear thinning and nonelastic) was similar to that of Phos-Chek, it differed in the latter stages in that the sheet maintained essentially its full width during the flow process, and then suddenly fractured along its entire width near the dowel. There was no evidence of liquid wrapping around the dowel during the impaction process for either fluid.

3.3.5.1 High Drop Height Tests

In the present program some early photographic studies were made of medium size drops impacting with a dowel after a 42 ft drop. Only off-center (non-central) impacts on the dowels were obtained in these tests, and one mirror was used so that only two views of the event were obtained. In one test shown in Figure 11, Phos-Chek XA was dropped on a 1/2 inch diameter polyethylene dowel. In this case the flow and subsequent necking fracture behavior of the liquid is the same as was observed in ref. 5, but the flow is not axially symmetrical. In several other tests Fire-Trol 931 was dropped on a 1/2 inch birch dowel. In these cases the flowing liquid sheet appeared to narrow slightly, and then fractured quickly in a manner similar to Fire-Trol 100 in ref. 5. These photographs were not suitable for duplication and are therefore not given here.

It may be seen in the pictures of Figure 11 that some liquid is initially present on the back lateral half of the dowel before the impact of the falling drop, which took place on the front lateral half of the dowel. This liquid was produced by an earlier impact of a drop of Phos-Chek XA which was not photographed. The liquid did not interfere with or affect the impact behavior of the drop given in Figure 11. It is however a good illustration of the general nature and form of the liquid that was retained on the polyethylene dowels after impact by the various retardants. The stringiness and localized area concentrations of the liquid can be compared with the relatively uniform stains produced on the birch dowel that are shown in Figure 9.

3.3.5.2 Low Drop Height Tests

Because most of the rheological effects in the liquid retention studies were observed at a low ($\sim$ 2 ft) drop height (hence low impact velocity), many of the photographic studies were also made at approximately this same height. As discussed before, the liquid retention of a medium sized drop of Phos-Chek XA impacting with a dowel after a 2 ft fall is significantly larger than for the other fluids, which were approximately the same. Figure 12 shows a few selected frames of a medium sized Phos-Chek XA droplet impacting on a 1/2 inch dry birch dowel after a drop of about 2-1/4 ft (giving an impact velocity of about 12 ft/sec). Two mirrors were used in photographing the impact and each picture gives the front, the top and the side view of the event. It may be seen that after impacting, the Phos-Chek XA drop flattens, and then flows laterally off the dowel in both directions in the form of a sheet. During the flowing the liquid elongates but does not fracture, and the side view shows that it does not wrap around the dowel. In the latter stages of the event, a maximum elongation is reached and the opposing ends are then pulled back towards the center of the dowel (the liquid narrows into a ligament during the pullback). This phenomenon can be better observed in Figure 13, which shows blowups of the corresponding sideviews of the event.

From the preceding pictures then it can be seen that the large (essentially 100%) retention of the Phos-Chek XA on the dowel after a low drop height (hence low impact velocity) impact is due to the fact that the initially-flowing liquid does not fracture, and is subsequently pulled back on the dowel by the elastic nature of the flowing liquid.

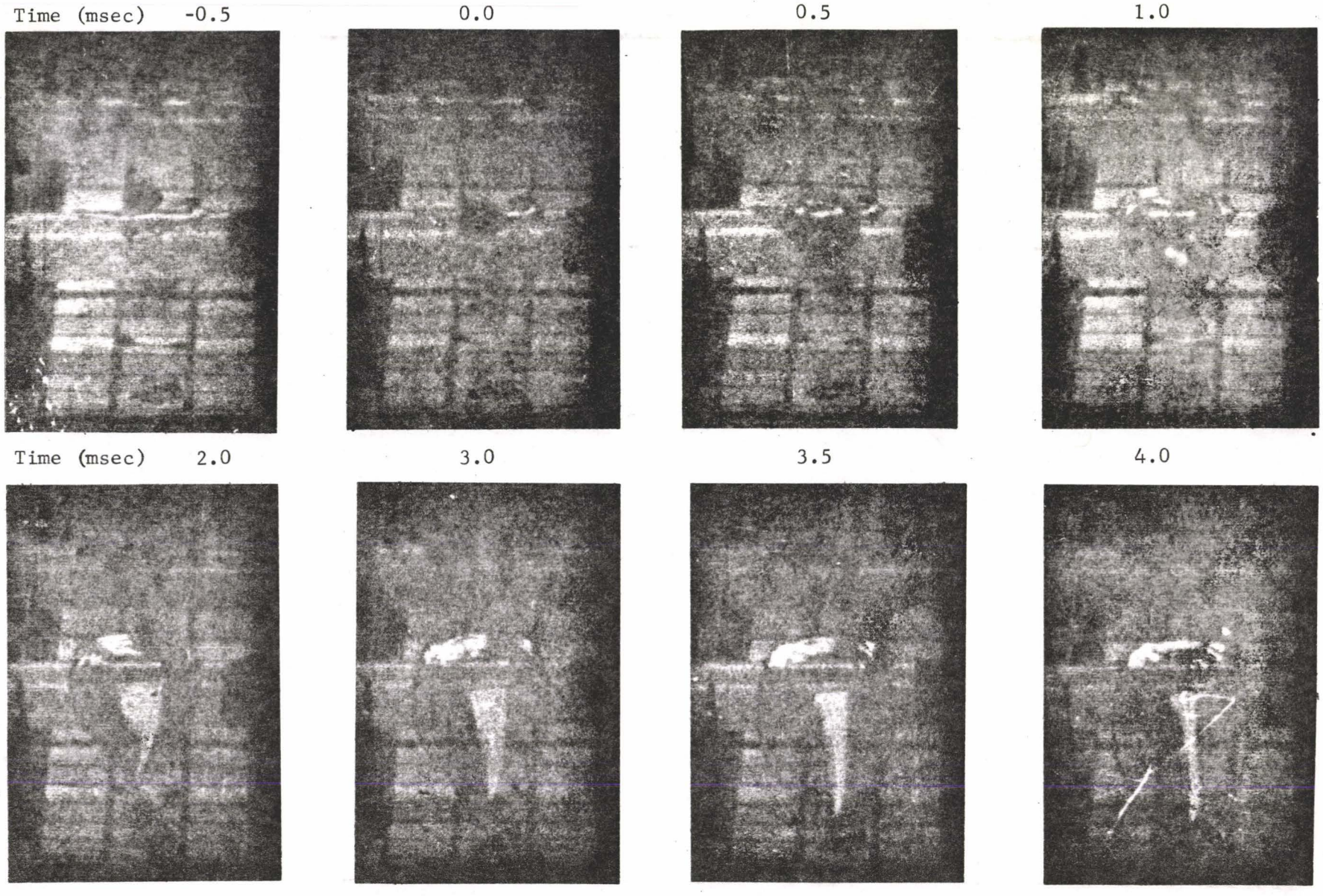


Figure 11. Selected Frames From the Impact of a Falling Drop (4.7 mm) of Phos-Chek XA With a 1/2 Inch Polyethylene Dowel. $V_i \simeq 26.5$ ft/sec.

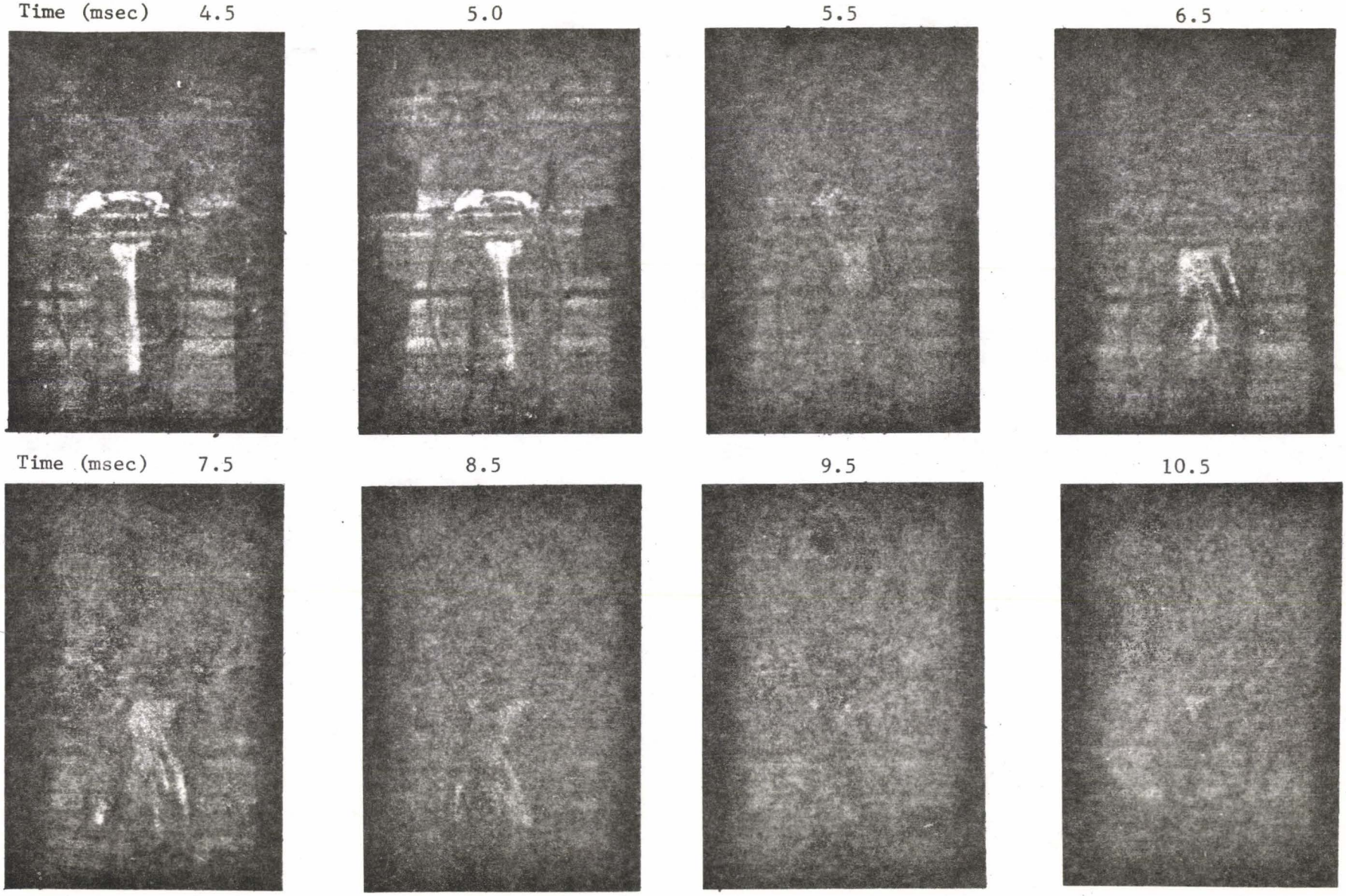


Figure 11. (Concluded) Selected Frames From the Impact of a Falling Drop (4.7 mm) of Phos-Chek XA With a 1/2 Inch Polyethylene Dowel. $V_i \simeq 26.5$ ft/sec.

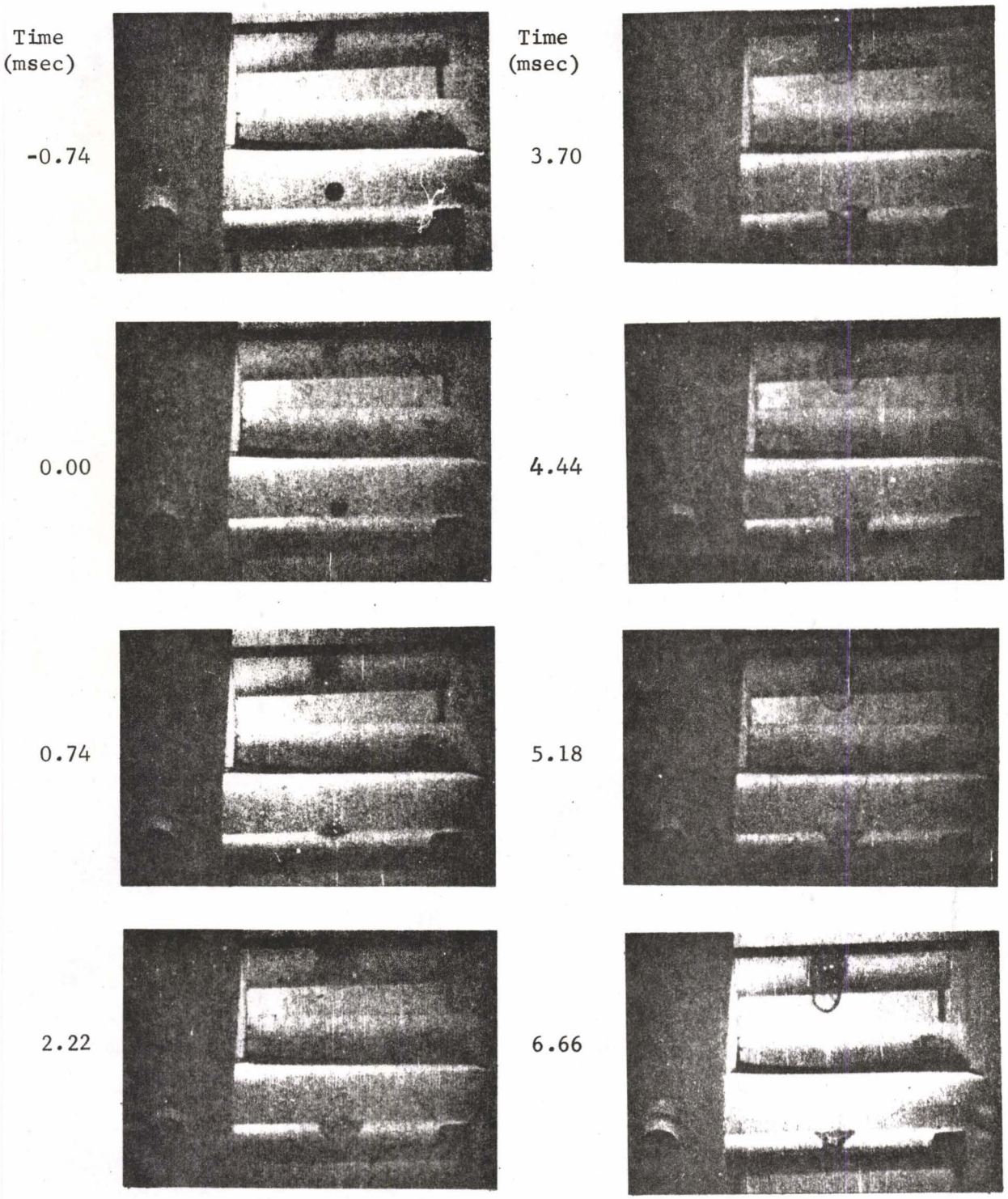


Figure 12. Selected Frames From the Impact of a Falling Drop (4.88 mm diam.) of Phos Chek XA With a 1/2 Inch Birch Dowel, V_i = 12.0 ft/sec.

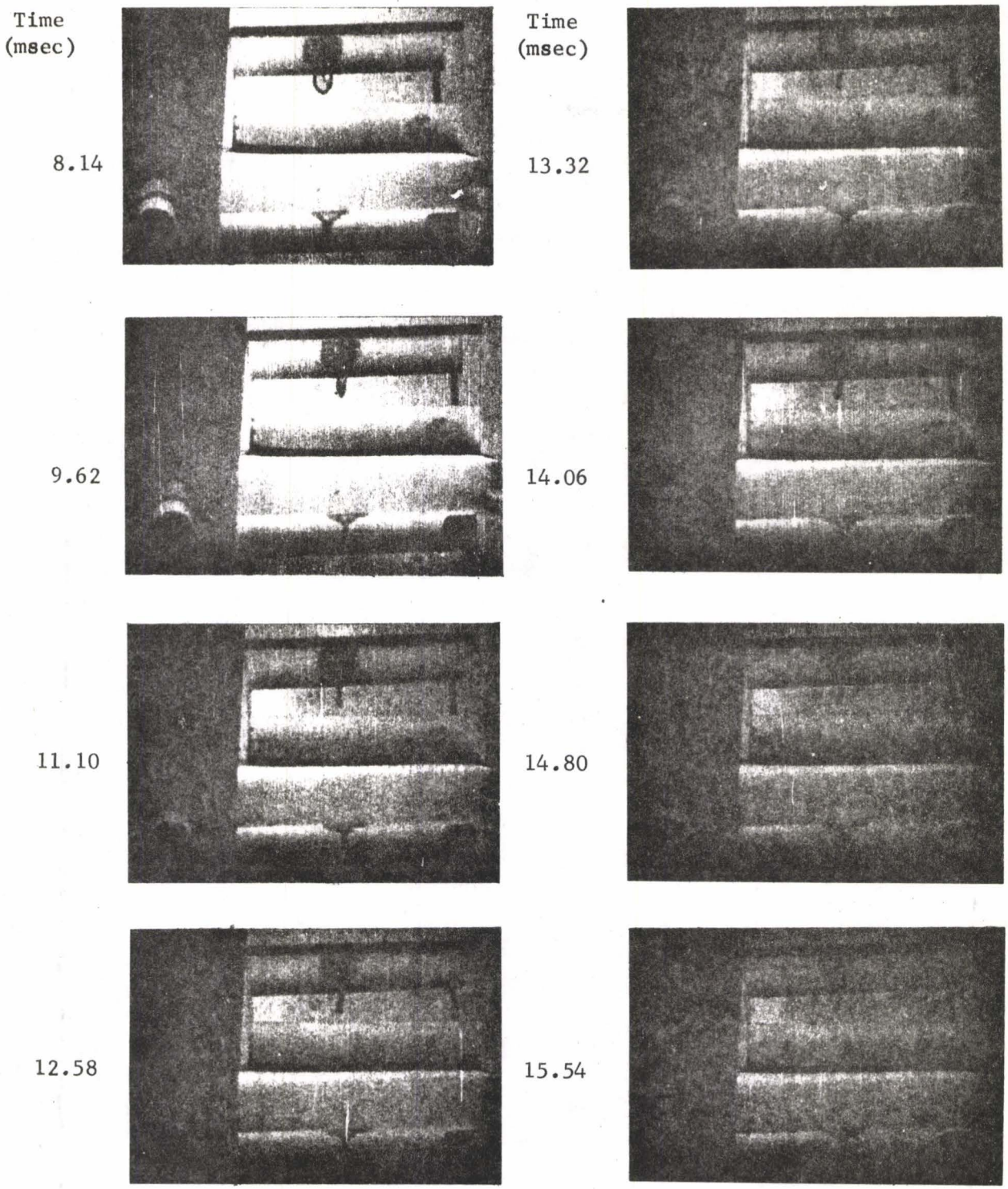


Figure 12. (Concluded).

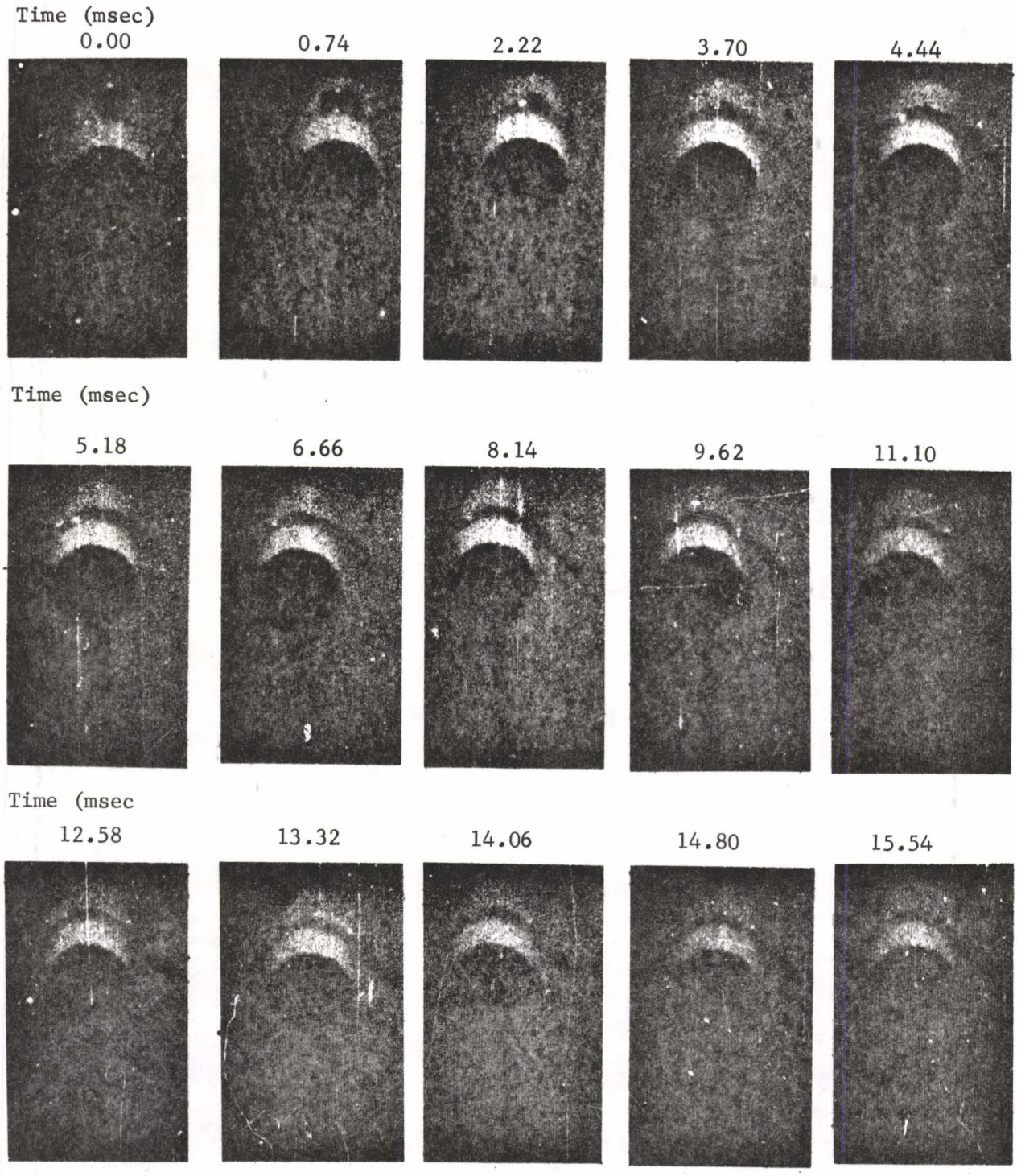


Figure 13. Blowups of the Side View Pictures of Figure 12.

On the other hand, high speed photographs of the impact of a drop of Fire-Trol 100 (Figure 14) and Fire-Trol 931 (Figure 15) impacting on a similar dowel at the same impact velocity show that in these cases after the impact the liquid initially flows and spreads in a similar manner to Phos-Chek, but subsequently fractures and sprays off the dowel. This results in a lower percentage of liquid being retained on the dowel, as was observed in the weighing experiments. Comparing the sideviews of Figure 13 with those of Figure 14 and Figure 15, it is observed that the Phos-Chek XA drop spreads and elongates at a larger angle from the top of the dowel than do the drops from the two Fire-Trol solutions.

3.3.5.3 Retention Efficiency vs Fuel Composition

From the results of Table II, it can be seen that the percent retention of water and the two Fire-Trol solutions on a 1/2 inch polyethylene dowel at 0° impact angle and a 2 ft drop height is significantly larger than it is on a 1/2 inch birch dowel. The retention of the Phos-Chek XA is about the same on both dowels and is near 100% (i.e., essentially all of the drop). It was seen in Figures 12 and 13 that the large retention efficiency of Phos-Chek XA on birch at low drop height is due to the fact that the initially-flowing liquid does not fracture, and is subsequently pulled back on the dowel by the elasticity of the liquid.

In order to obtain further information regarding the differences of the effect of dowel composition on the retention efficiency of the other liquids, a photographic sequence was taken of the impact of a drop of Fire-Trol 100 impacting with a 1/2 inch polyethylene dowel. Selected frames are shown in Figures 16 and 17. It is seen in this case that as the drop impacts and flattens out, the flowing liquid wraps around the dowel, which increases its retention efficiency. This was the first evidence of liquid wrap-around during impact that has been observed, although it has often been speculated on - particularly for an elastic liquid (Fire-Trol 100 is a nonelastic liquid). Interestingly enough, the wrap-around was not observed for the impact of Phos-Chek XA with the polyethylene dowel, as may be seen in Figures 18 and 19. Thus it would appear that the retention efficiency of polyethylene is larger than that of birch because its composition or surface properties in some manner causes the impacting drop to come in contact with a larger surface area of the dowel. As to whether this is also true in the case of water and Fire-Trol 931 has not been determined photographically, but the splatter patterns (discussed in the next section) suggests that it is.

3.3.6 Discussion of the Splatter Patterns

As discussed in Section 3.2.2, an impactor card was placed centrally below the dowel in the various impact tests to obtain information regarding the splatter pattern of the liquid produced by drop impact with the dowel and the effects of the various parameters.

3.3.6.1 Off-Center Versus Central Impact

The central impact of a drop on a dowel results in an essentially symmetric splatter pattern of liquid being produced on both sides of the dowel, whereas an off-center impact produces an unsymmetric pattern. The general characteristics of the liquid splatter and its pattern depend both on the properties of the liquid and the impact position on the dowel.

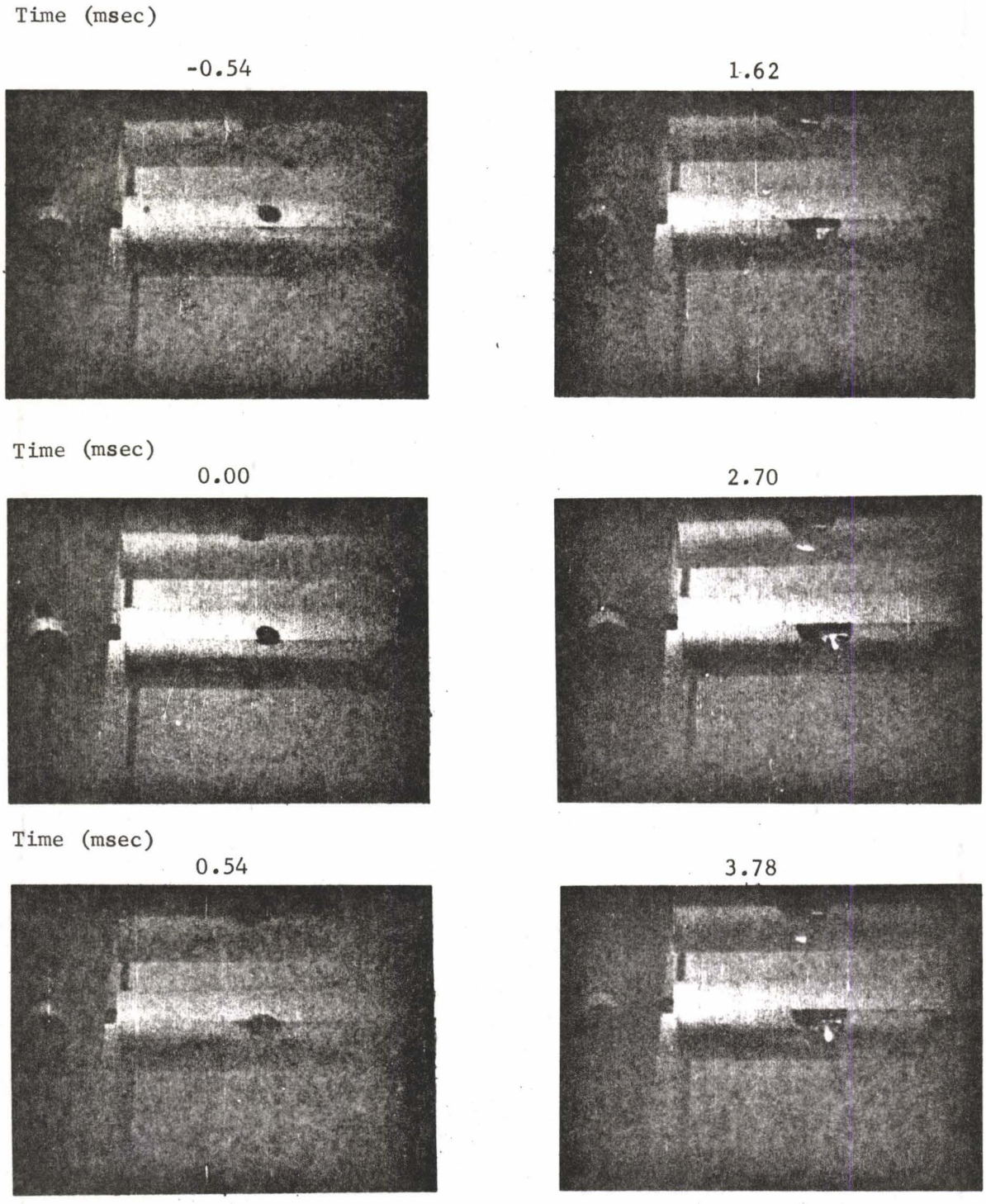
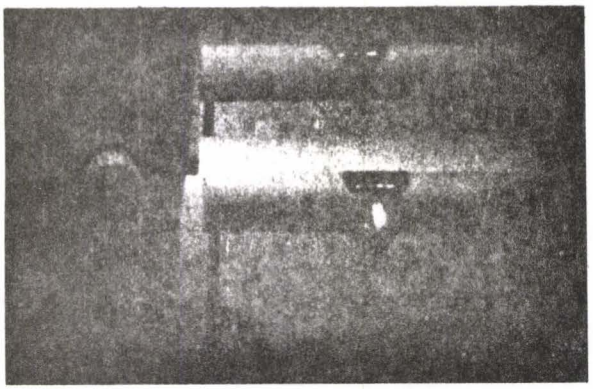


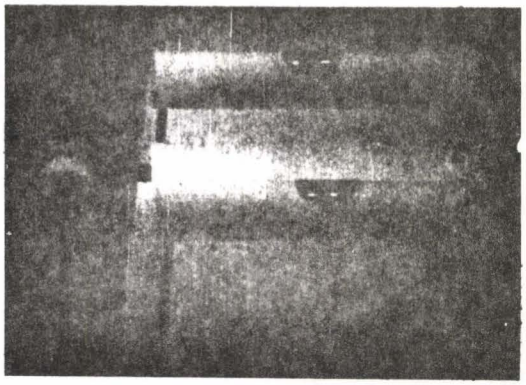
Figure 14. Selected Frames From the Impact of a Falling Drop (4.9 mm diam.) of Fire-Trol 100 With a 1/2 Inch Birch Dowel, V_i = 12 ft/sec.

Time (msec)

5.94

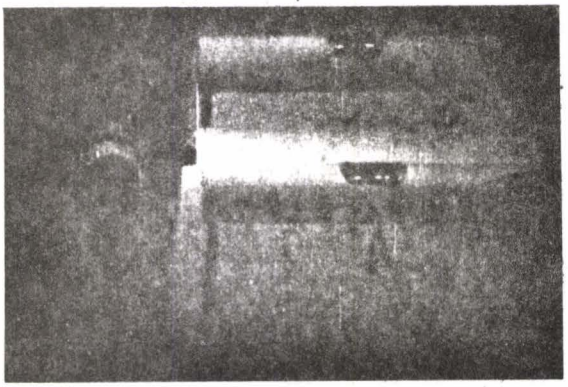


11.34

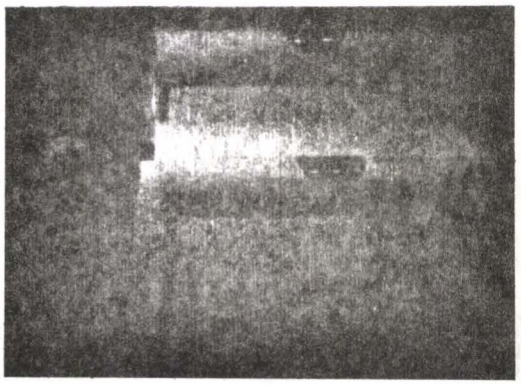


Time (msec)

8.10

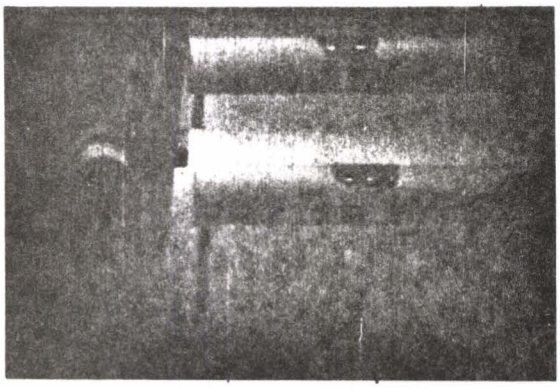


14.58



Time (msec)

10.26



19.98

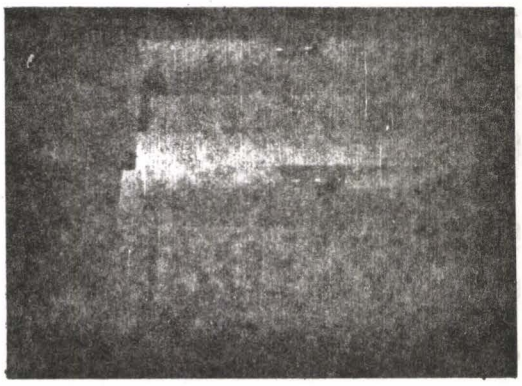


Figure 14. (Concluded).

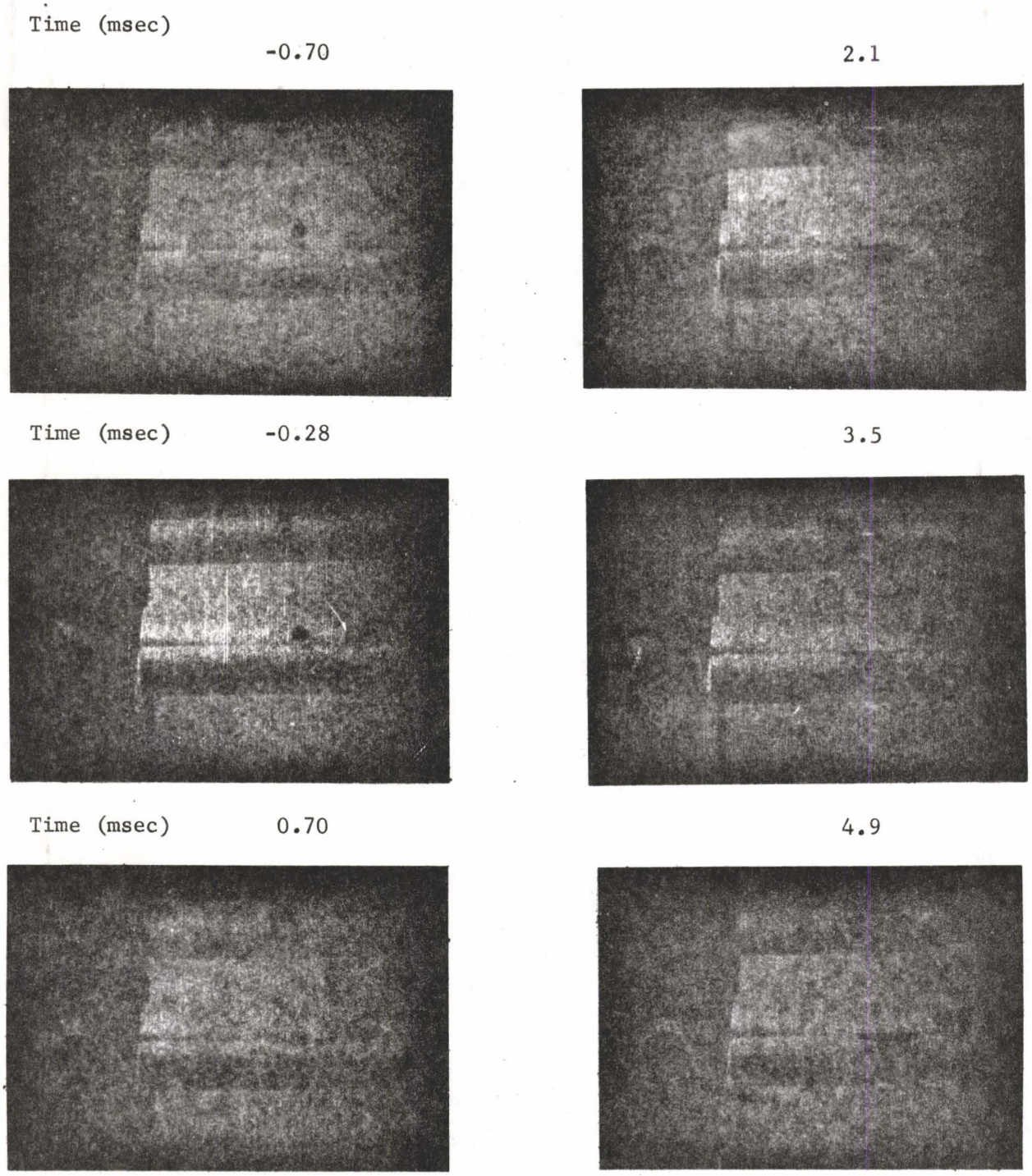
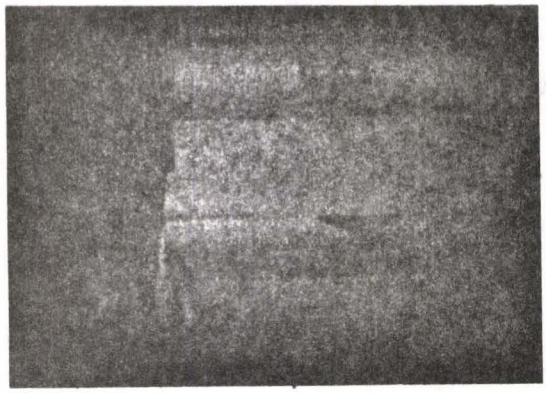


Figure 15. Selected Frames from the Impact of a Falling Drop (4.5 mm diam.) of Fire-Trol 931 With a 1/2 Inch Birch Dowel, V_i = 12 ft/sec.

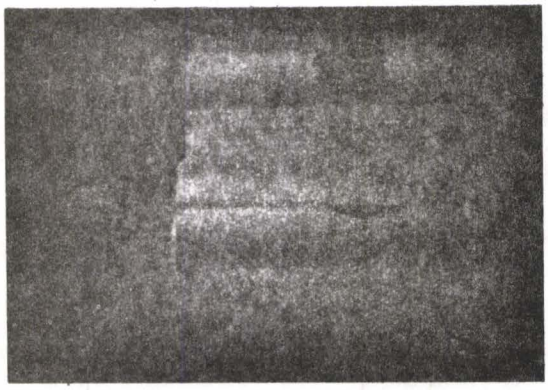
Time (msec)

6.3



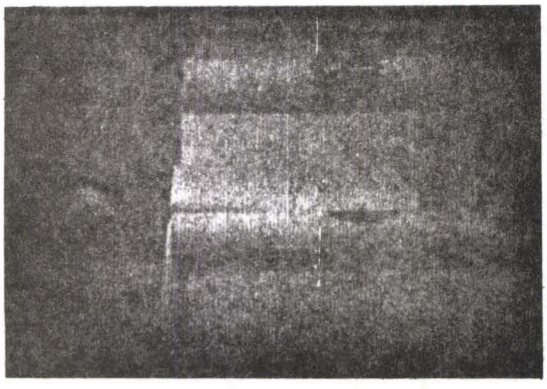
Time (msec)

7.7

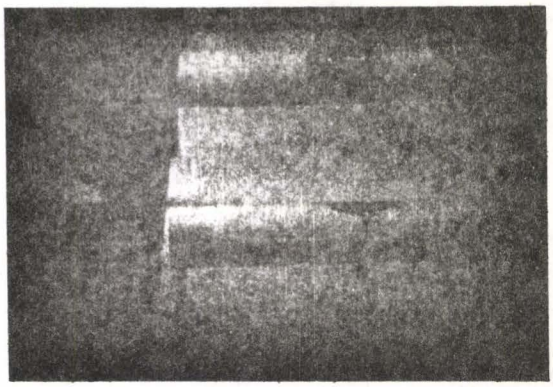


Time (msec)

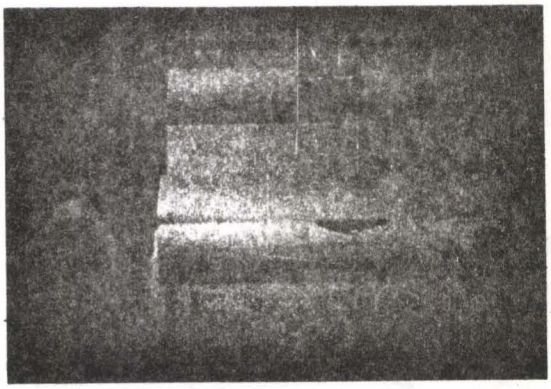
9.1



10.5



11.9



13.3

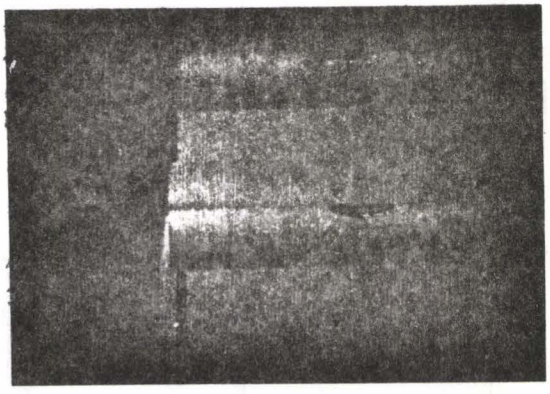


Figure 15. (Concluded).

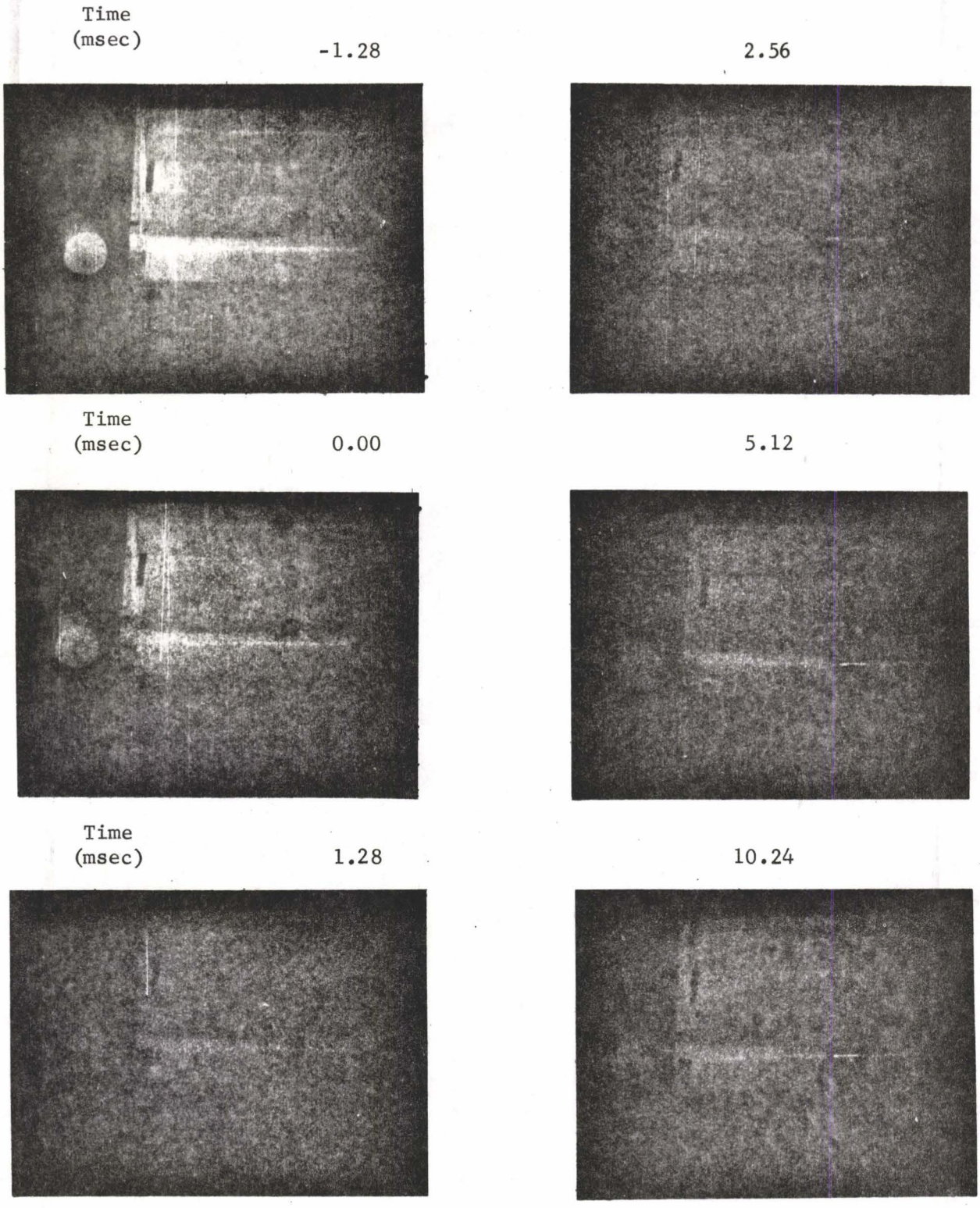
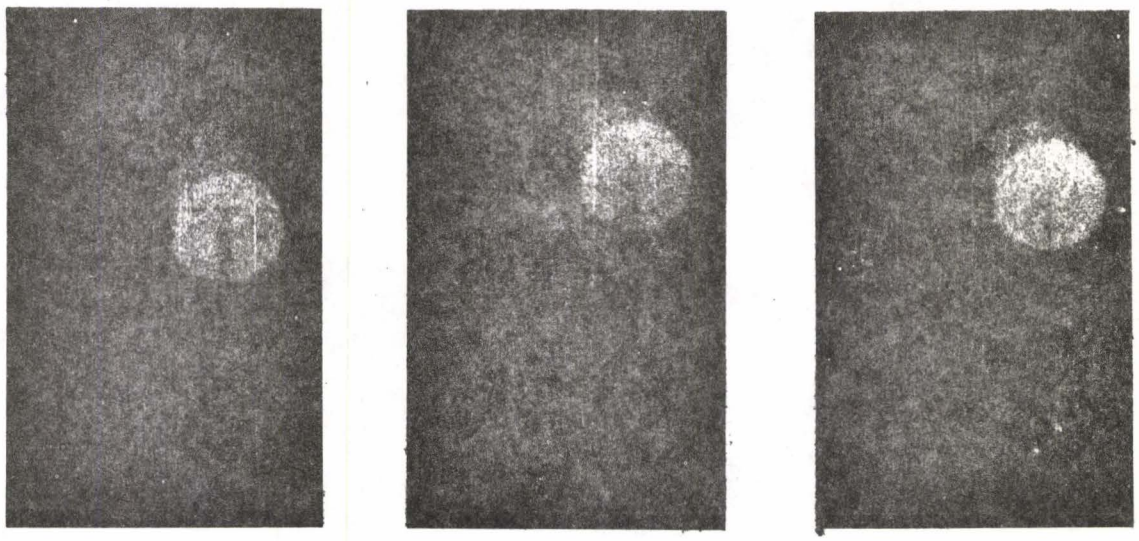


Figure 16. Selected Frames from the Impact of a Falling Drop (4.9 mm diam.) of Fire-Trol 100 with a 1/2 Inch Polyethylene Dowel, V_i = 12 ft/sec.

Time (msec)

-1.28 0 +1.28



Time (msec)

2.56 5.12 10.24

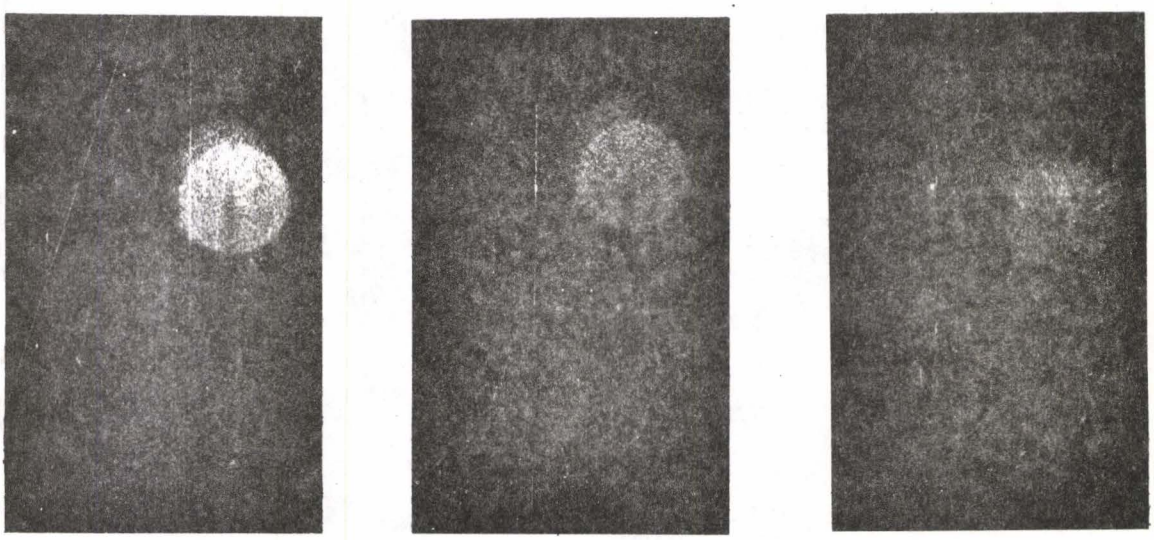


Figure 17. Blowups of the Side View Pictures of Figure 16.

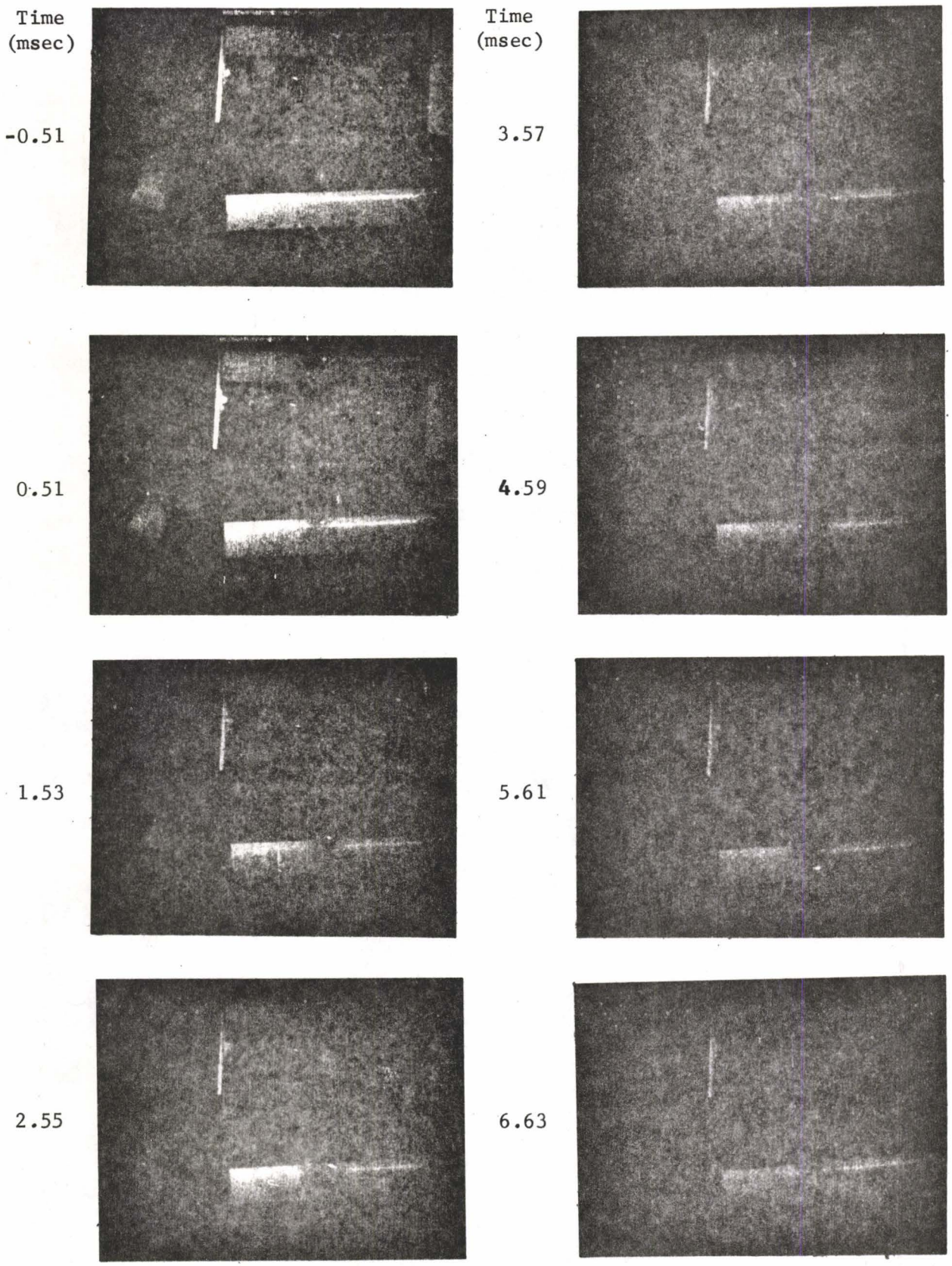


Figure 18. Selected Frames From the Impact of a Falling Drop (4.8 mm diam.) of Phos-Chek XA with a 1/2 Inch Polyethylene Dowel, V_i = 12 ft/sec.

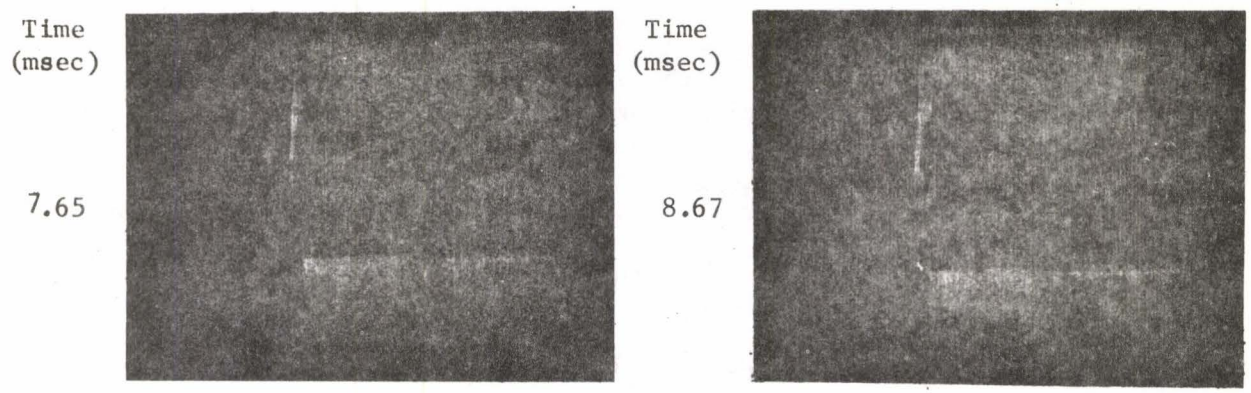


Figure 18. (Concluded).

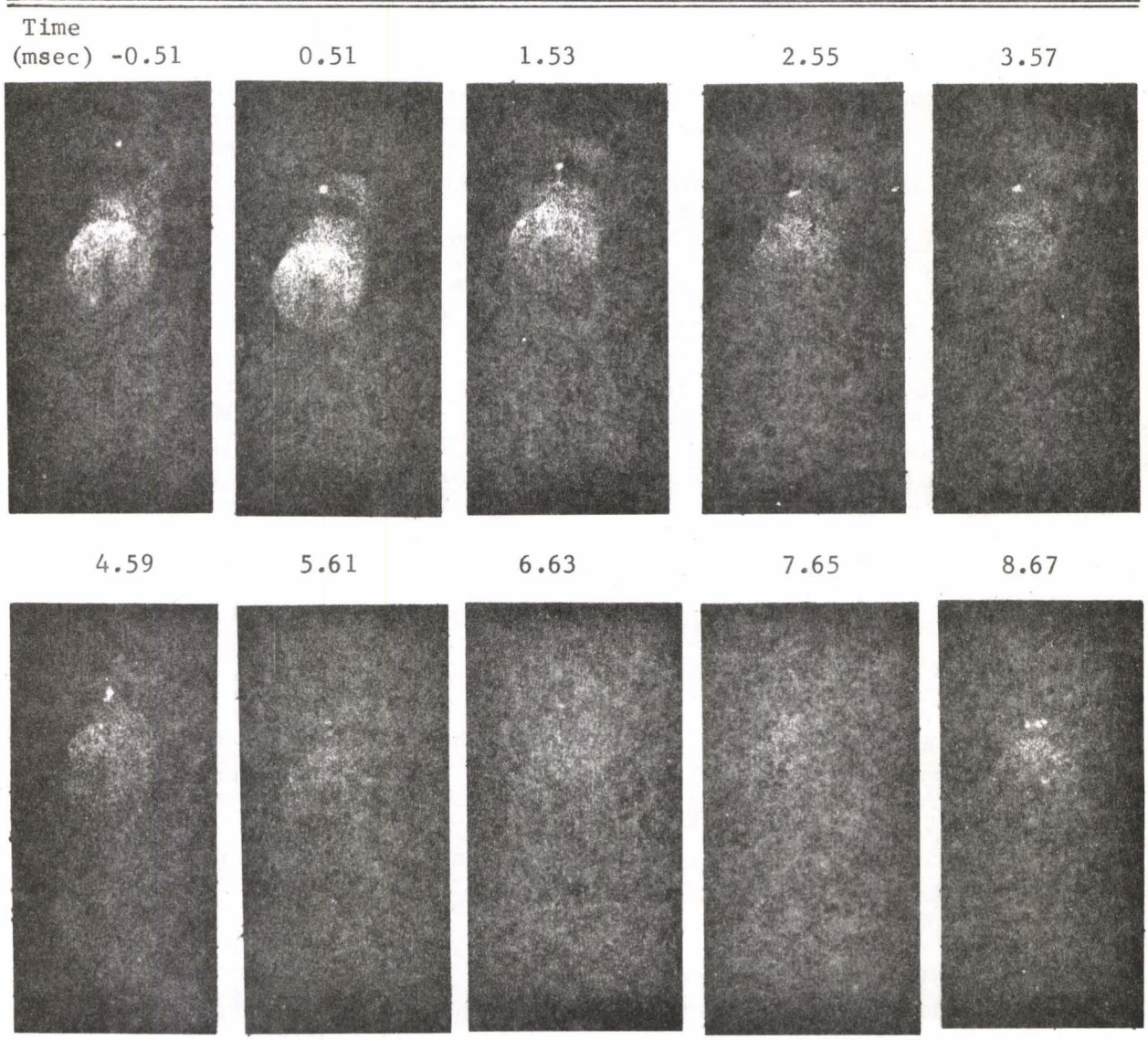


Figure 19. Blowups of the Side View Pictures of Figure 18.

Figure 20 shows the splatter patterns for a sequence of impacts ranging from grazing (large off-center) impact to central (axial) impact for Fire-Trol 931. Above each pattern is given the percentage of liquid retained on the dowel (the remainder is on the splatter card). At just grazing impact (the first picture) little breakup of the drop occurred on the dowel, which resulted in a nearly compact splotch being produced on the impactor card on one side of the dowel. The fraction of the liquid retained on the dowel was very small. The splotch produced on the impactor card is close to the dowel and is nearly representative of a free-falling drop except for a small degree of lateral flow and jetting (shown by the spikes and rays) imposed on the outward side of the pattern by the impact.

As the impact position of the drop on the dowel moves toward the axis, i.e., becomes more central, the splotch position on the card moves outward away from the dowel, and the percentage of liquid retained on the dowel increases. The size of the splotch generally decreases, and the pattern exhibits increased effects of outward fluid jetting, breakup and spray formation. Numerous fragments of liquid of various sizes (including many small particle spots lost in the photographic reproduction process) are produced. The degree of liquid breakup increases as the impact point becomes more central. As the impact point approaches the axial (central) position, some liquid splatter also appears on the opposite side of the dowel. For a completely central impact, the liquid becomes completely broken up into droplets by the impact and the splatter pattern of the droplets is essentially symmetrical on both sides of the dowel.

3.3.6.2 Effect of Fluid Composition

The general characteristics of the splatter patterns shown in Figure 20 for Fire-Trol 931 were also obtained for Fire-Trol 100 and water. However, the patterns obtained from Phos-Chek XA differed in that they were always compact and little breakup of the liquid into small droplets occurred, even for central impact (Figure 21). This is quite likely the result of the elastic behavior of the liquid. Figure 22 compares the splatter patterns of a medium sized droplet of the retardants impacting centrally with a 1/4 inch birch dowel. The difference in splatter pattern between Phos-Chek XA and the other three solutions is well illustrated here.

3.3.6.3 Effect of Dowel Size and Composition

Figure 23 shows a comparison of the splatter patterns produced by medium sized drops of water, Fire-Trol 931 and Phos-Chek XA impacting centrally with a dry 1/4 and 1/2 inch birch dowel (the drop height was 42 ft). The patterns of each retardant are essentially the same for both size dowels, except that the pattern is displaced further away from the axis for the larger diameter dowel. Thus dowel size has little effect on the liquid spray produced by impact.

Figure 23 also shows a comparison of the splatter patterns produced by drops of the preceding retardants impacting with 1/2 inch birch and polyethylene dowels. For Phos-Chek XA there is no significant difference between the patterns produced by the two different composition dowels. For each dowel the splatter pattern consists largely of a single coherent blotch

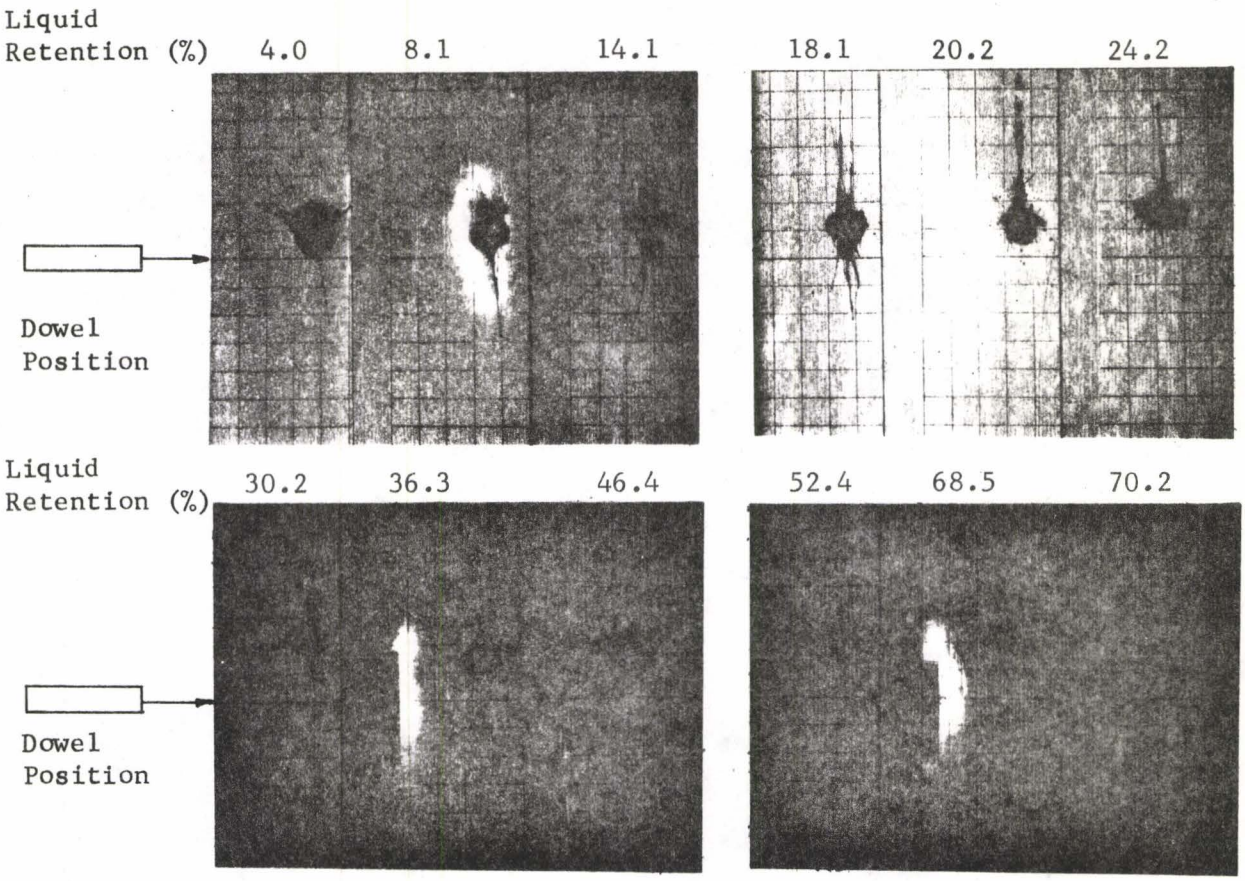


Figure 20. Splatter Patterns of Off-Center versus Central Impacts of a Falling Drop of Fire-Trol 931 (4.4 mm diam.) on a 1/2 Inch Polyethylene Dowel (Drop Height = 42 ft).

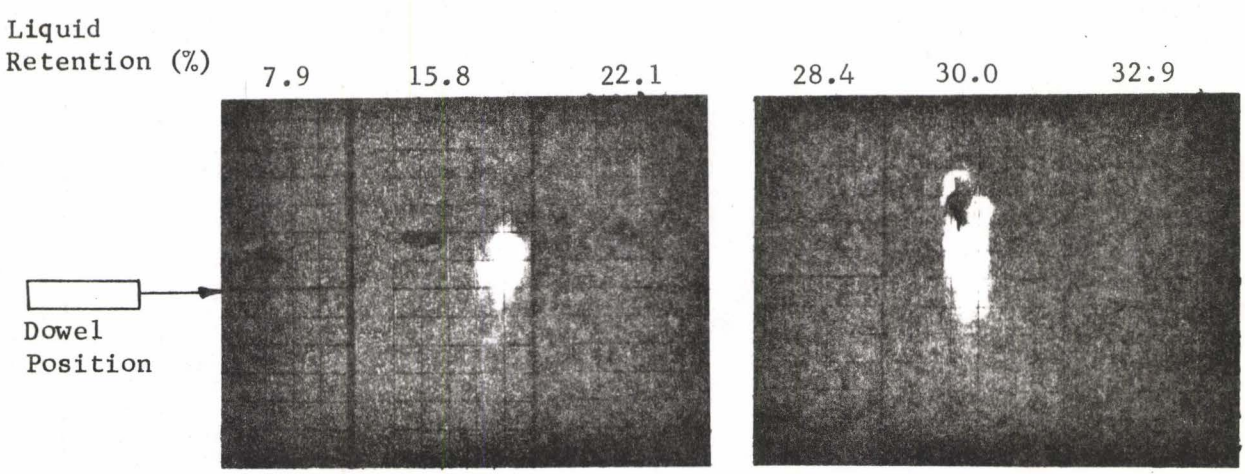


Figure 21. Splatter Patterns of Off-Center versus Central Impacts of a Falling Drop of Phos-Chek XA (4.8 mm diam.) on a 1/2 Inch Birch Dowel (Drop Height $\simeq$ 42 ft).

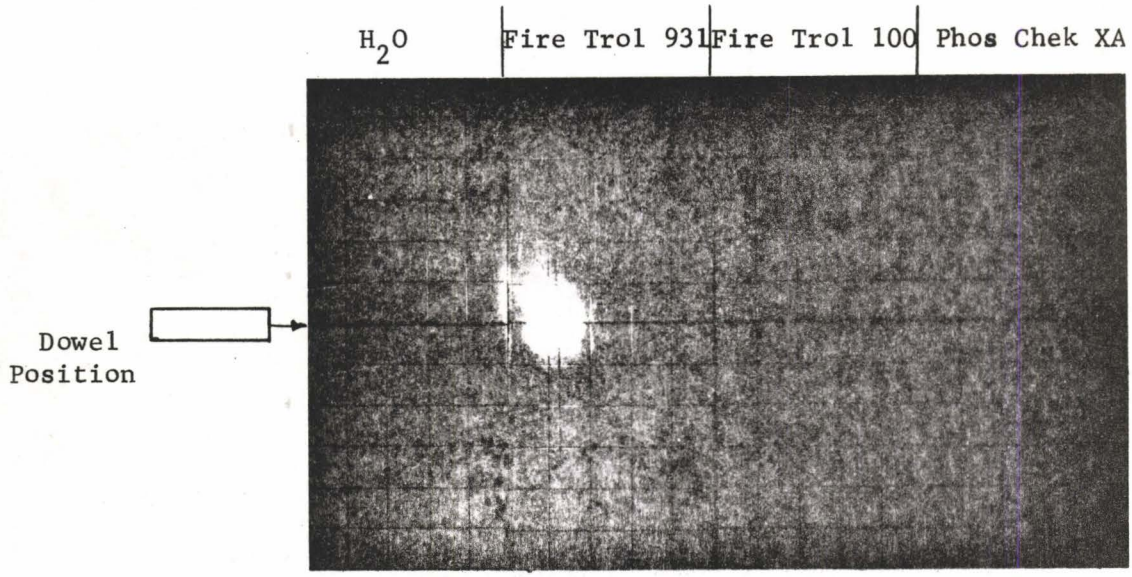


Figure 22. Splatter Patterns of Falling Drops of the Retardants (4.2-4.9 mm diam.) Impacting Centrally With a 1/4 Inch Birch Dowel, Drop Height = 42 ft.

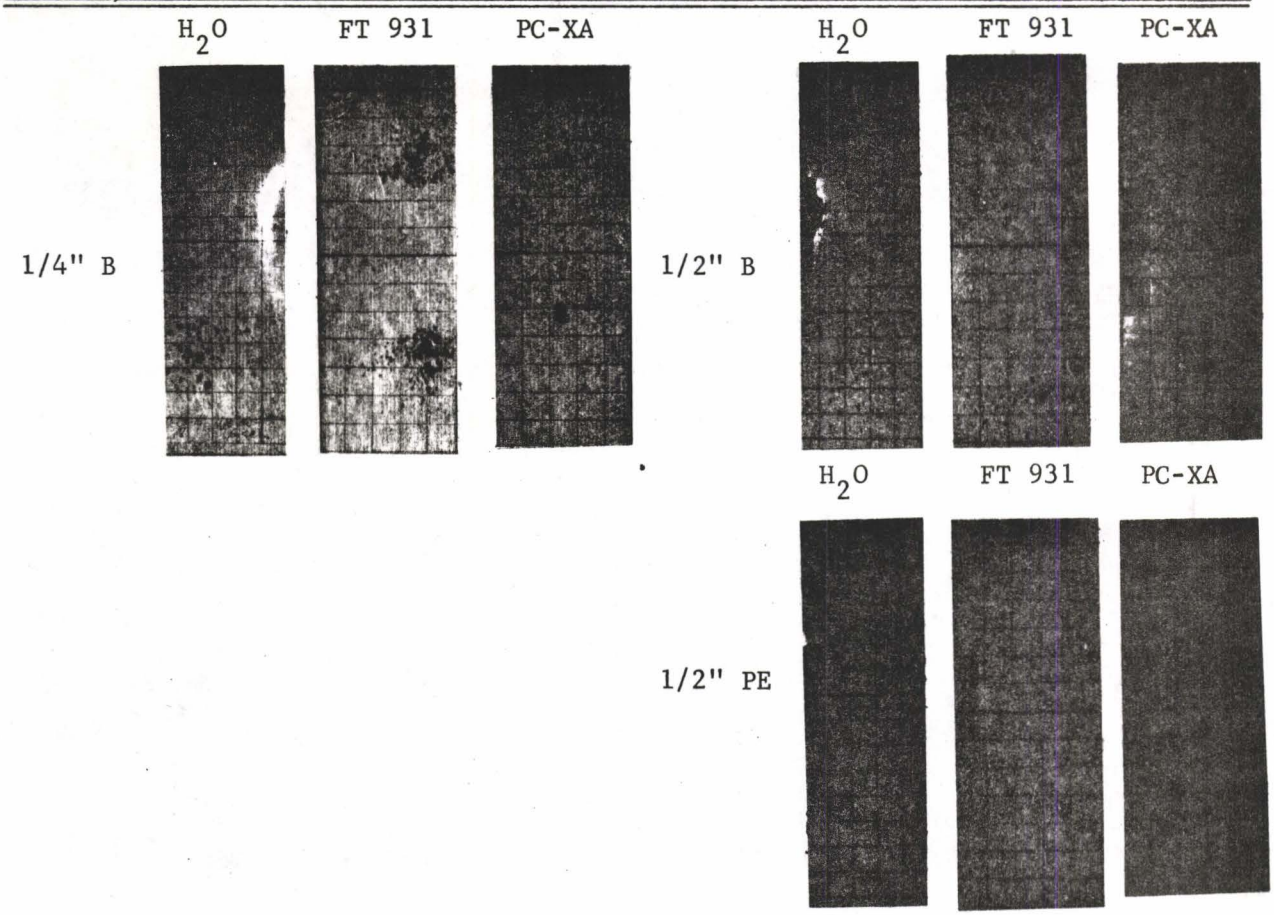


Figure 23. Splatter Patterns of Falling Drops of Retardants (4.2-4.8 mm diam.) Impacting With 1/4 and 1/2 Inch Birch and 1/2 Inch Polyethylene Dowels. Drop Height = 42 ft.

located symmetrically on each side of the dowel. In some cases there was also one or two small additional satellite blotches but never fine spray splatter. The immediate region around the dowel was always free of splatter.

On the other hand the splatter patterns of water and Fire-Trol 931 (also Fire-Trol 100) consisted of spray (droplet) splatter rather than coherant masses, as discussed previously. In the case of the birch dowels this splatter was located, symmetrically, at some distance from both sides of the dowel axis. However, for the polyethylene dowel the spray splatter from water and Fire-Trol 931 drops also extended inward underneath the dowel (to its axis) on both sides of the dowel (Fire-Trol 100 was not dropped on the polyethylene dowel at 42 ft). This indicates that the liquid flow over the dowel during impact penetrates over a larger circumferential area for the polyethylene dowel than for the birch dowel. This behavior may be due to the smoothness (low surface friction) of the polyethylene dowel, and appears to occur only with the low viscosity (including shear-thinning) liquids.

Since the splatter pattern for Fire-Trol 100 with the polyethylene dowel was not obtained, it is not known whether it is similar to that of water and Fire-Trol 931. In this case however, the high speed photographs given in Figures 16 and 17 showed that the Fire-Trol 100 had a tendency to wrap-around the polyethylene dowel. Since the liquid retention of Fire-Trol 100 is about the same as that of Fire-Trol 931 and water, this would seem to indicate that the wrapping effect found for Fire-Trol 100 also occurs for Fire-Trol 931 and water, and results in the ejection of spray droplets immediately below the dowel (fuel) as well as from its sides.

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